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SURGERY

VOL. 37 JANUARY, 1955 No. 1

Original Communications

Society for Vascular Surgery

CONSIDERATIONS AND PHYSIOLOGIC STUDIES IN THE CLOSURE OF INTERAURICULAR SEPTAL DEFECTS*

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THE interauricular septal defect is one of the more common single congenital defects occurring in the human heart, and the successful closure of this lesion, with restoration of normal cardiopulmonary hemodynamics, constitutes a significant surgical achievement. In an attempt to perfect a safe and effective method of closure, an exhaustive amount of detailed and highly ingenious effort has been expended within the past decade. In this report, we wish to present our experiences with the surgical closure of this deformity in a series of eighteen patients.

A review of the various approaches to the problem of closure of atrial septal defects, both experimental and clinical, might be considered. In 1947, Cohn[1] first demonstrated experimental closure of artificially produced atrial defects by invaginating and suturing a portion of the right atrial wall to the edges of the defect. The stalk formed by this procedure was then severed and the defect in the atrial wall repaired. Although this method was never used clinically, Bailey and co-workers[2] utilized the principle of this closure in apposing and suturing the right atrial wall to the rim of septal defects. They did not divide the stalk, however, and added the procedure of digital guidance by the introduction of the ungloved finger into the right auricle through the right auricular appendage. To this method Bailey has given the name "atrio-septo-pexy."

We wish to acknowledge the assistance of Thomas Nolan, B.S., and Norman Bleicher, B.A., laboratory technicians.

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An additional closed method of repairing atrial septal defects, by means of pericardial grafts, was reported by Shumacker[3] in 1953. He attached a hemisphere of pericardium, constructed from a detached portion, to an incision in the right atrial wall, thus increasing the redundancy of the latter. The pericardial area was then invaginated against the septal defect without digital guidance, then sutured to the defect rim, a method similar to that used by Cohn. Although this operation was uniformly successful in dog hearts, the autogenous pericardium unfortunately failed to remain viable in human beings.

Murray, in 1948,[4] reported a method of apposition of the anterior and posterior atrial walls in the plane of the septum. This was effected by the passage of mattress sutures of silk or fascia, entering the site of the transverse sinus behind the aorta and emerging posteriorly between the superior vena cava and the right pulmonary veins. Although one patient subjected to this procedure was improved, the uncertainty of even partial closure of a defect prevented acceptance of this method. Bailey and co-workers,[5] however, used Murray's principle in part, in conjunction with the atrio-septo-pexy method for the closure of septum primum defects, and mentioned that the combined procedure may prove independently corrective in cases of very large septal defects or where a single atrium is present.

In 1953, Björk and Crafoord[6] reported a modification of a technique described to them by Sondergaard. The first step in this procedure is the dissection of a groove between the superior vena cava and the pulmonary veins. A finger is then inserted through the right auricular appendage for digital guidance of a large, thin needle, introduced through the right auricular wall close to the origin of the aorta and immediately behind the right coronary artery. With the finger following as it passes endocardially, the needle is introduced through the upper portion of the interventricular septum and brought out through the left side of the septum posteriorly behind the inferior vena cava close to the annulus fibrosus. The two ends of the silk sutures are then tied in the dissected groove.

In 1953, Gross and Watkins[7] described a closed method for the repair of septum secundum defects by the introduction of sutures through the posterior wall of the right auricle, to include the anterior rim of the defect, the suture emerging near its point of entry. They pointed out that this method may, in addition, be used to shift the septal wall to the right of anomalous pulmonary veins, thus restoring pulmonary drainage to the left auricle, as well as closing the septal defect. Also in 1953, Neptune, Bailey, and Goldberg[8] described a method of introducing sutures from the exterior, guided digitally within the right auricle, for the correction of atrial defects associated with transposition of the pulmonary veins. This method is an application of Bailey's atrio-septo-pexy principle and consists of suturing the atrial wall to the defect in such a manner that a small, isolated chamber is created in the right auricle which communicates the septal defect and therefore the left auricle with the anomalous veins.

Closure of atrial septal defects by invagination of the auricular appendages into the openings was first proposed by Swan and co-workers[9] in 1950. Buttons placed externally on the auricular appendages were apposed through the defect and held in this position by heavy sutures passing through them. Experience with this method revealed that it shared the disadvantages inherent in other closed techniques, since it could not be determined accurately if the shunt had been closed or if there had been encroachment upon the orifices of other vessels. Swan, in 1953,[10] reported a modification of this method in which a finger is placed in the right auricle through the right auricular appendage. Digital guidance is thus afforded for a ligature probe which is passed from the left auricular appendage through the septal rim and the right appendage. Another suture is similarly placed, passing through the opposite rim of the defect. A button is then attached to the suture on the right and pulled into the interior of the right auricle against the septal defect. The opposite rim of the defect. A button is then attached to the suture on the right appendage. In 1950, Santy and associates[11] described a method of plugging the atrial defect by inverting the tip of one auricular appendage through it.

Additional methods of occluding atrial defects by interior devices have been reported. In 1951, Hufnagel and Gillespie[12] reported a method of utilizing a double button which is introduced by an instrument that screws together the buttons on each side of the defect. For the occlusion of artificially made defects in dogs, this method was satisfactory; however, unsatisfactory results in three patients convinced Gross[13] that the method was unsafe for human operations, where septal rims are likely to be incomplete. Kiriluk, Hoag, and Merendino,[14] in 1951, described a method of closure by creating a small plug of autogenous fat sutured within the pericardium and drawing this into, and thus tamponading, the defect. In the same year, Martin and Essex[15] described a method of introducing small sheets of plastic material through the atriums of dogs, those being held in place by passing the sutures out to the exterior in the plane of the septum. Gross[16] utilized a rubber well attached to an incision in the right auricle for the introduction of interrupted sutures or plastic sheets for the obliteration of septal defects, the plastic being attached to the edges of the defects by sutures introduced through the cone of blood. In an experimental modification of Gross's ingenious method, Shumacker,[17] in 1953, reported a method of inserting a graft through a rubber-capped glass cylinder which had been sutured into the right atrial appendage.

Inherent disadvantages in the closed methods of correcting atrial septal defects led investigators to study techniques whereby the defects may be closed under direct vision. Swan[18] and his associates attempted to close artificially produced atrial defects in dogs by occlusion of the venae cavae and opening of the right auricle for brief periods of time. Martin and Essex[19] used the same procedure in the process of creating atrial septal defects, also in dogs. In 1952, Cookson, Neptune, and Bailey[20] reported the use of hypothermia in conjunction with venae cavae occlusion and opening of the right auricle in a patient for the attempted repair of an atrial septal defect. The patient de-

veloped ventricular fibrillation, however, and expired. In 1953, Lewis and Taufic[21] reported the first successful closure of an auricular septal defect in a child by using hypothermia, occlusion of the venae cavae, and wide opening of the right auricle. These investigators and others have used this method successfully in other patients.

In an effort to gain more time for the closure of atrial defects by an open method than that afforded by hypothermia and occlusion of the venae cavae, considerable effort has been expended in an attempt to shunt all blood successfully from the heart and lungs into an extracorporeal circuit. This experimental work was pioneered by Gibbon and his associates.[22, 23] Mustard and Chute[24, 25] and Glenn and Sewell[26] have reported successful closure of artificially produced atrial septal defects in dogs using extracorporeal circulations. Dennis and co-workers[27] first reported the attempted closure of a large atrial septal defect in a human patient, a desperately ill child, by utilizing a pump oxygenator to replace the heart and lungs, but unexpected difficulties led to the expiration of the patient. A similar attempt made in another patient a few weeks later also ended fatally. Helmsworth and associates[28] reported in 1953 their unsuccessful application of the pump oxygenator to a patient thought to have an atrial septal defect. An interventricular defect was found instead and closed. The patient expired, however, either from anoxia or cerebral air embolism.

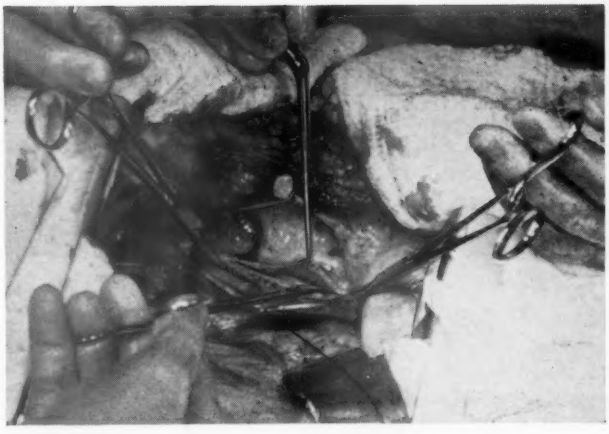
Total cardiac by-pass, employing the azygos flow principle with mechanical perfusion and an autogenous lung lobe as the oxygenator, has been recently reported by Cohen and Lillehei.[29] By this procedure a large, interventricular septal defect was exposed by a right ventricular cardiotomy and successfully closed by interrupted silk sutures placed under direct vision.

TECHNICAL CONSIDERATIONS

Atrio-septo-pexy and the atrial well method have been used to close the auricular septal defects in this group of patients. The patient is anesthetized with endotracheal anesthesia and placed supine with the right side elevated to approximately twenty degrees. The chest is entered through an incision beginning at the right border of the sternum and extending over the course of the fourth intercostal space to the posterior axillary line. The fourth and fifth costal cartilages are usually incised adjacent to the sternum. The pericardium is incised anterior to the phrenic nerve (Fig. 1, *A*), and a purse-string suture is placed about the base of the right auricular appendage. The finger is introduced into the auricle through an incision in the appendage and the position and extent of the defect determined. If feasible, the atrio-septo-pexy is performed. If not, the incision in the appendage is closed and the well is sutured to a long incision in the posterior aspect of the auricle (Fig. 1, *B* and *C*). About 200 to 400 c.c. of strained citrated blood is placed in the well, depending upon the size of the patient, and the clamps on the auricular wall are released (Fig. 1, *D*). Sufficient time is allowed for cardiac action and blood pressure to become stable before intracardiac manipulations are performed. The defect is then sutured together with interrupted silk sutures (Fig. 1, *E*).

The sutures are first placed and then tied (Fig. 1, *F*). At this point one usually notices that the blood's level decreases and its color becomes much darker. The well is then compressed and elevated to return part of the blood to the circulation, and the clamps are reapplied to the auricle immediately below

A.



B.

Fig. 1.—*A*, The chest has been entered through an anterolateral incision in the right fourth intercostal space and the pericardium has been incised anterior to the phrenic nerve, exposing a markedly enlarged right auricle.

B, Curved ductus clamps have been applied to a portion of the right auricular wall and an incision is being made into the auricular wall within the clamps.

C, The rubber well has been sutured to the incision in the right auricle.

D, The clamps have been removed from the right auricle and the well has filled with blood.

E, A suture is being placed in the anterior rim of the defect.

F, The sutures have been placed across the defect and are being tied, thus closing it.

G, The well has been removed and the incision in the auricle has been closed.

the well's attachment to it. The well is then excised and the incision in the auricle is closed with a row of continuous and interrupted mattress sutures (Fig. 1, *G*). The pericardium is reapproximated loosely with interrupted silk.

C.

D.

E.

F.

G.

Fig. 1, *C-G.* (*For legend see page 5.*)

The chest is closed and water-seal drainage is instituted. Throughout the operation a few cubic centimeters of a 1 mm. per cubic centimeter solution of heparin is injected around the edges of the well periodically to prevent clotting.

RESULTS AND DISCUSSION

A total of eighteen patients were operated upon in this series. Of this group, seventeen had a defect in the septum secundum and one had a septum primum defect with an associated deformed mitral valve. Two of those with septum secundum defects had partial transposition of the pulmonary veins. The ages of this group of patients range from 6 to 46 years. Six were male and twelve were female.

All of these patients complained of easy fatigability. Dyspnea was present to some degree in sixteen of them and was moderate to severe in eleven. Con gestive failure had been present or was present in eight and had been severe in two. One was in failure at the time of operation. Cyanosis was not present in any of the patients at the time of operation, but one gave a history of cyanosis at birth (Table I). Cardiac catheterization was performed in all but one of these patients before operation, and a pulmonary arterial pressure of over 50 mm. of mercury was present in five. Two additional patients, not included in this series, were found to have other anomalies at the time of operation. One had complete transposition of the pulmonary veins entering into the right innominate vein and one had an Ebstein's deformity of the tricuspid valve.

TABLE I

NO.	PATIENT	AGE (YR.)	SEX	CARDIAC FAILURE	DYSPNEA	EXCESSIVE FATIGABILITY	CYANOSIS	SIZE OF DEFFECT (CM.)	RESULTS	METHOD OF CLOSURE
1	I. B.	43	F	++	++	++	0	Good	5	AW
2	B. P.	15	F	0	+	+	+ (birth)	Good	5	AW
3	M. B.	6	F	++++	+++	++++	0	Expired	4	AW
4	J. B.*	8	F	++	++++	++++	0	Unim-proved	4 × 5	AW
5	L. M.	12	F	0	+	++	0	Good	4	AW
6	J. M.	8	F	0	+	+	0	Good	3	AW
7	D. M.	10	M	0	+	+	0	Good	2	AW
8	L. F.	42	F	++	++	++	0	Good	5	AW
9	F. D.†	16	F	0	++	+	0	Good	2 × 2	AW
10	J. B.	46	M	0	++	++	0	Good	3	AW
11	C. D.	7	F	0	0	+	0	Good	3	AW
12	G. M.	36	F	+++	+++	++++	0	Expired	5	AW
13	C. M.	19	F	0	++	++	0	Good	5	AW
14	R. M.	27	M	+	+++	++	0	Good	5 × 7	AW
15	R. J.	7	M	0	+	+	0	Good	2	ASP
16	C. B.	22	F	++	++	++	0	Good	5	ASP
17	W. C.‡	31	M	++	++	++++	0	Expired	5	AW
18	J. W.‡	11	M	0	0	++	0	Good	2	ASP

AW = Atrial well.
ASP = Atrio-septo-pexy.
*Large septum primum defect: mitral insufficiency.
†Two defects, 2 cm. in diameter.
‡Transposed pulmonary veins to right auricle and superior vena cava.

The atrial well was used in fifteen patients, and atrio-septo-pexy was employed in three. In one of the latter group, transposed pulmonary veins were

present on the right, two entering the superior vena cava about 3 cm. above its entrance, and two entering into the right auricle itself. A high septal defect was present so that a pocket could be formed to include the openings of the two veins which entered the auricle and extended up along the superior vena cava to include the two veins emptying into it. This maneuver reduced the superior vena cava to about one-half of its original diameter for a distance of 3 cm. An anomalous left superior vena cava, however, was known to be present. In another patient, who had transposed right pulmonary veins, the well method was employed and the anterior rim of the septum was sutured to the right of the veins' entry into the wall of the right auricle, thereby causing them to drain into the left auricle. Two defects were found in only one patient, each measuring 2 cm. in diameter.

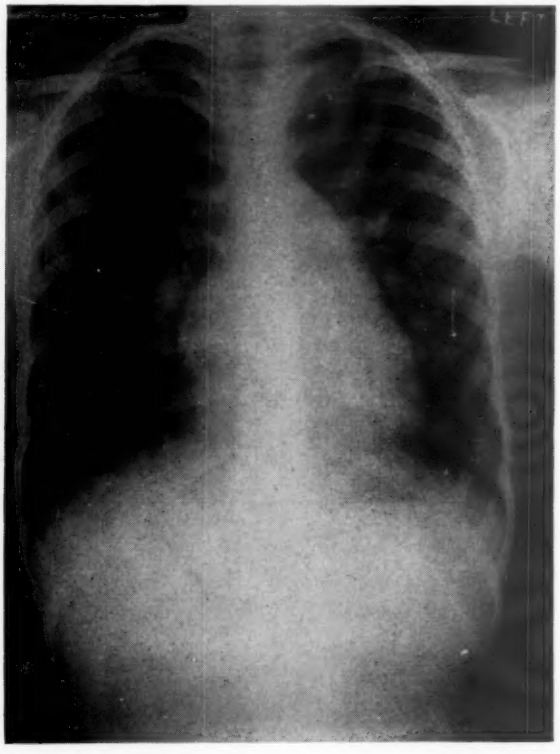


Fig. 2A.—X-ray film of chest before operation on Patient L. M., demonstrating cardiac enlargement.

When the atrial well procedure was used, the defect was closed by directly suturing the edges of the defect together in fourteen of the fifteen patients treated with the atrial well. In one patient, J. B., an 8-year-old child, a septum primum defect and deformity of the mitral valve were found. A nylon, plastic patch was sutured to three sides of the defect, but no tissue could be found between the valves to which it could be anchored inferiorly. It was thought that the shunt might be reduced and the patient improved if this patch were left in place; however, about one week later severe heart failure developed. At a second operation, three weeks later, the well was reapplied to the auricle

and it was found that the high left auricular pressure resulting from regurgitation through the deformed mitral valve had shifted the lower end of the patch to partially cover the tricuspid valve. The patch was removed and the patient has now returned to the preoperative status.

During the operation on one patient, J. B., a 46-year-old man, the heart rate suddenly became quite rapid and the level of blood in the well rose considerably. The procedure was quickly completed and it was found later that a spontaneous pneumothorax had occurred on the left side. The air was removed and his convalescence was uneventful.

Fig. 2*B*.—X-ray film of chest two and one-half months after operation on Patient L. M., demonstrating decrease in heart size.

In only one patient, R. M., was the level of blood in the well so high that it overflowed when the hands were introduced to close the defect. Only by submerging the hands slowly beneath the surface of the blood, so that the excess could drain off into the pulmonary circulation, was excessive blood loss over the top of the well prevented. This patient had the largest defect encountered in the series.

Good clinical results were obtained in fourteen patients. Evaluation has been based upon a decrease in the heart size (Fig. 2) and the disappearance of dyspnea, excessive fatigability, and cardiac failure. Cardiac catheterization is planned in the near future on all of the patients who have survived. Three operative deaths have occurred in this series. Two were in adults,

aged 31 and 36, who had severe pulmonary hypertension, and one in a patient, aged 6, who had been in severe heart failure for about two years and was in failure at the time of her operation. The atrial well was employed in the treatment of these patients. Two patients, aged 8 and 10, who were brother and

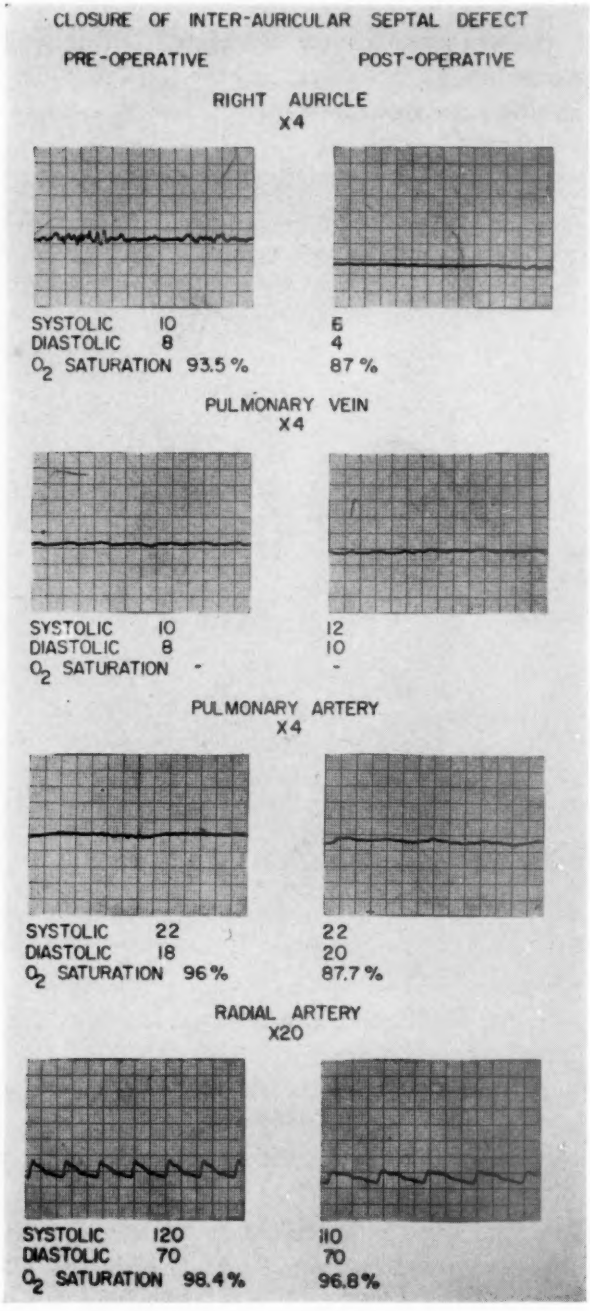


Fig. 3.—Pressure tracings and oxygen saturation studies made during operation before and after the defect was closed. The pressure in the right auricle and the O_2 saturation in the right auricle and the pulmonary artery diminished following the closure of the defect.

sister, developed fever, chest pain, and increased cardiac dullness, beginning about two months after their operations. X-ray films showed evidence of pericardiac effusion. They were treated with antibiotics and improved temporarily. Approximately four months after operation, however, Patient D. M.'s temperature rose to 103° to 104° F. and was spiking in character, in spite of the administration of penicillin and Terramycin. Pericardial aspiration yielded no frank pus, and a pericardiotomy was performed through an incision in which portions of the left third and fourth costal cartilages were resected. The pericardium was found to be markedly edematous and thickened, but no frank suppuration was present. Dense adhesions between the pericardium and heart were freed. A hemolytic *Staphylococcus aureus* cultured from the pericardium was found to be sensitive to penicillin. Twenty million units of penicillin were given intravenously each day for two and one-half months, resulting in the patient's recovery with no further evidence of pericarditis.

TABLE II. PRE- AND POSTOPERATIVE PRESSURES

PATIENT	AGE (YR.)	RIGHT AURICLE		RIGHT VENTRICLE		PULMONARY ARTERY		PULMONARY VEIN OR LEFT AURICLE		AORTA, BRONCHIAL OR RADIAL ARTERY	
		PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
J. B.	46	6 1-2	--	22-25 4-6	--	18 13	--	10 6	—	110 70	--
F. D.	16	5-6 2	6 4	15-18 1-4	10-13 2	15-17 12	17-18 15	6-7 4	11-8 7	100 70	110 80
C. D.	7	10 8	6 4	35 15	26 11	22 18	22 20	10 8	12 10	120 70	110 70
L. F.	42	6 4	4-6 2-3	40-44 12-14	16-17 6-7	40 28	24 17-18	6-8 4	14-16 9-11	90 70	105-110 80-90
R. J.	7	10-12 7-8	9-11 1-3	36-38 2-4	21-24 0-2	29-31 18-19	20-23 8-10	14-15 9-10	10-12 0-4	125-130 89	112-115 70
D. M.	10	6-10 0-2	13-15 6-8	90-100 0	--	26-28 12-20	24-26 16-18	6-16 0-2	16 8-9	125-130 70	120-125 60-65
J. M.	8	10-11 7-8	8 2	40-42 4-6	40-45 0-2	32-34 26-28	44-46 36-40	14 10	16-18 12	125-130 65	145 70
D. M.	19	5 4	8 7	21 2-3	20 7	24 16	16 12	8 7	9 5	125 80	120 85
R. M.	27	8-9 0-1	13-15 0-2	40-45 7-10	30-33 7-9	46-50 33-35	40-42 26-27	18-20 8-10	8-9 0-1	127-130 85	120 83
L. M.	12	3-10 0-3	6-8 1-3	--	--	40 19-20	20-22 10-11	9-10 4-5	11-12 6-7	110-115 70-75	120 80-85

Pressures were measured in the cardiac chambers immediately before and after the defect was closed (Fig. 3). It was noted that the pressure usually fell in the right auricle, right ventricle, and pulmonary artery, and rose slightly in the left auricle and aorta (Table II). Blood samples were likewise removed immediately before and after the defect was closed and generally

showed a fall in the oxygen saturation of right auricular, right ventricular, and pulmonary artery blood, and no change in that of the left auricle (Table III). Blood volume determinations, made by the T 1824 dye method, on five patients immediately before and two weeks after their operations indicated a diminished volume after the defect was closed.

TABLE III. PRE- AND POSTOPERATIVE PER CENT OXYGEN SATURATION

	SUPERIOR VENA CAVA		RIGHT AURICLE		PULMONARY ARTERY		PULMONARY VEIN OR LEFT AURICLE		AORTA, BRACHIAL OR RADIAL ARTERY	
PATIENT	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
M. B.			95	—	98	—	100		98.5	—
J. B.	—	76	94.5	72.5	93	68.7	99	98	96.8	—
F. D.			88.3	83	85.5	80	93.9	94	94	94
C. D.	—	85.7	93.5	87	96	87.7	96.8	98	98.4	96.8
L. F.	—	80.4	96.8	81	96.3	81.7	97.5	98	97.5	98
R. J.	—	81	90.9	86.3	92.2	80	95.9	100	99.8	—
D. M.	—	90.3	91.5	93	91	91	95	98.3	95.5	97.5
J. M.	—	82.8	91	82.1	89.9	81	92.5	93.3	93	—
L. M.	—	94.1	99.9	93.7	98.5	93	98	99.8	99.8	—
D. M.	—	71.8	86.3	81	89.8	78	94.2	97	90.7	96.6
R. M.	—	83	98.2	87	98	88.5	99	98.2	—	98.6

Although our experience has been primarily with the atrio-septo-pexy and atrial well procedures, several methods of closure seem satisfactory. Bailey's method has the advantage of being technically simple and therefore well tolerated by poor-risk patients. In our experience, however, an appreciable number of defects cannot be completely closed by this technique, although where one can identify a rim of septal tissue, particularly inferiorly and anteriorly, in which to place the sutures, the procedure can usually be performed.

The Gross method, employing the atrial well, is more tedious and time consuming. It has certain advantages, however, in that it is an open, direct operation and allows adequate time to explore the interior of the auricle. We have noticed that the blood pressure often drops to a low level shortly after the clamp on the auricle is removed. The citrated blood placed in the well before the clamps are removed often presents this drop from occurring. If a significant decrease should occur, however, the introduction of blood rapidly through a cannula in the radial artery usually re-establishes a satisfactory pressure. There has been no difficulty with bleeding at the point of the well's attachment to the auricle or with air or blood embolism. Pulmonary hypertension probably increases the risk of operation, regardless of what method is used, and patients having severe pulmonary hypertension tolerate the well poorly. The three patients who died had the highest pulmonary artery pressures in our series.

The open method, under hypothermia and employing vena caval occlusion, thereby producing a bloodless field and direct vision of the defect, is ideally the best procedure. It has the disadvantage, however, of placing the surgeon under pressure by limiting the time he has to close the defect. The open method also increases the possibility of air embolism, particularly in the coronary arteries. Control of air embolism has been achieved by placing a

noncrushing clamp across the aorta and pulmonary artery immediately above their origins, and also by flooding the chest with saline solution before the auricular incision is closed, as Swan has advocated. In addition, ventral fibrillation is more likely to occur under hypothermia when a cardiotomy is performed. Crafoord's method also offers the advantages of being technically simple and may allow one to close septum primum defects.

Present operative procedures offer reasonably safe and satisfactory closures for most atrial defects. An open visual method is more ideal than a blind one, and will probably become the procedure of choice as soon as certain technical and physiologic problems associated with methods employing hypothermia and extracorporeal heart-lung apparatus have been solved. In addition, severe septum primum defects and atrioventricularis communis defects, which cannot be closed by existing methods, may be repaired when an open visual technique is employed.

SUMMARY

A review of the development of procedures for the closure of interauricular septal defects is presented. A series of eighteen patients is reported, on whom the atrio-septo-pexy or atrial well method of closure of defects was performed. The defect was closed in fourteen patients, all of whom obtained good clinical results. The defect was not closed in one patient who had a large septum primum defect and a deformed mitral valve. Three operative deaths occurred. The results of pressure studies and oxygen determinations immediately before and after the defect was closed are recorded. Blood volume determinations immediately before and two weeks after operation are reported in five patients. Technical considerations and complications arising in the treatment of this group of patients are discussed.

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THE EXPERIMENTAL PRODUCTION AND CORRECTION OF MITRAL INSUFFICIENCY

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EXPERIMENTAL and clinical attempts by others to correct mitral insufficiency have been directed principally toward utilization of one or both deformed valve cusps, by means of a variety of ingenious suture, leaflet replacement, and prosthetic techniques. Bailey has summarized many of these methods, ranging from pericardial slings beneath the valve to direct suture of the valve leaflets.[1] Harken has employed plastic prostheses inserted to act as a baffle during systole,[2] and modifications of this approach have been reported by other investigators.[3, 4] Attempts to mobilize and suture the leaflets have also been described, including the breaking up of adhesions and selective cutting of shortened chordae tendineae following adequate commissurotomy.[5]

A motion picture analysis of the mode of action of the mitral valve in the living dog, carried out in this laboratory in 1951, demonstrated that closure of the valve orifice involves two coordinated components.[6] While closure is completed by apposition of the valve leaflets, a significant narrowing of the lumen is effected by the systolic sphincterlike contraction of the annulus. The present report is concerned with efforts to apply this latter observation by utilizing the annulus in an attempt to correct experimentally induced mitral insufficiency in dogs.

EXPERIMENTAL METHOD

The Surface Anatomy of the Mitral Annulus.—In order to establish the optimum site for plication of the mitral annulus in the present study, it was necessary to clarify the precise projection of the valve ring on the epicardial surface of the heart, with particular reference to the coronary arteries. It is commonly accepted that the circumflex coronary artery is located immediately superficial to the mitral annulus; verification of this relationship would indicate that operative maneuvers in this area might compromise the arterial blood supply to the myocardium. Mitral stenosis has been simulated successfully in the dog in other laboratories by passing sutures through and around the auricle just above the valve,[7, 8] and speculation concerning possible human application of such techniques in the correction of mitral insufficiency has been recorded.[9]

A series of dissections was undertaken in normal human* and dog hearts with the purpose of defining the surface projection on the heart of the mitral

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Fig. 1.—*A*, Position of mitral annulus relative to circumflex coronary artery; *B* and *C*, surface projections of anterior and posterior commissures.

annulus and the commissures. The valve ring was located uniformly a few millimeters below the circumflex coronary artery; that is, the vessel was slightly further from the apex of the heart than was the annulus. The surface topography of the anterior commissure was situated in the angle formed by the junction of the circumflex and the anterior descending coronary arteries. The posterior commissure was similarly located with respect to the angle present at the origin of the posterior descending coronary artery (Fig. 1). Whether or not these relationships may be altered as the heart is distorted by rheumatic infection, as described by Grant,[10] was not investigated. It was demonstrated, however, that plication of the mitral annulus may be accomplished anatomically in the normal heart, without jeopardizing the coronary vessels, by sutures strategically placed in the left ventricular myocardium.

Creation of Mitral Insufficiency.—Techniques for producing and correcting mitral insufficiency, and for evaluating the results of these procedures, were explored in a series of twenty-eight mongrel dogs, of either sex, weighing from 21 to 80 pounds. All operations were performed under anesthesia maintained by a standard veterinarian solution of Nembutal administered intravenously. The left pleural cavity was entered by an anterolateral incision through the fourth intercostal space, and respirations were maintained by a pump rhythmically delivering oxygen under positive pressure through an intratracheal tube. The pericaridum was incised vertically, anterior to the phrenic nerve, and the pericardial flaps held apart with traction sutures. A purse-string suture of heavy silk on an Atraumatic needle was passed around the base of the left auricular appendage, a nonerushing clamp placed distal to this, the tip of the appendage amputated, and all trabeculae in the field divided. Insertion of the right index or fifth finger permitted palpation of the mitral valve and completed the preliminary steps.

Initially it had been thought that mitral insufficiency could be created by vigorous digital dilatation of the orifice and manipulation of the leaflets. The intracardiac finger could detect a strong systolic jet after such trauma had been inflicted, and palpation after placing the correcting sutures uniformly disclosed that the jet was gone. It was soon appreciated, however, that a jet so produced would disappear spontaneously within a few minutes, as the elasticity of the normal heart overcame the dilatation.

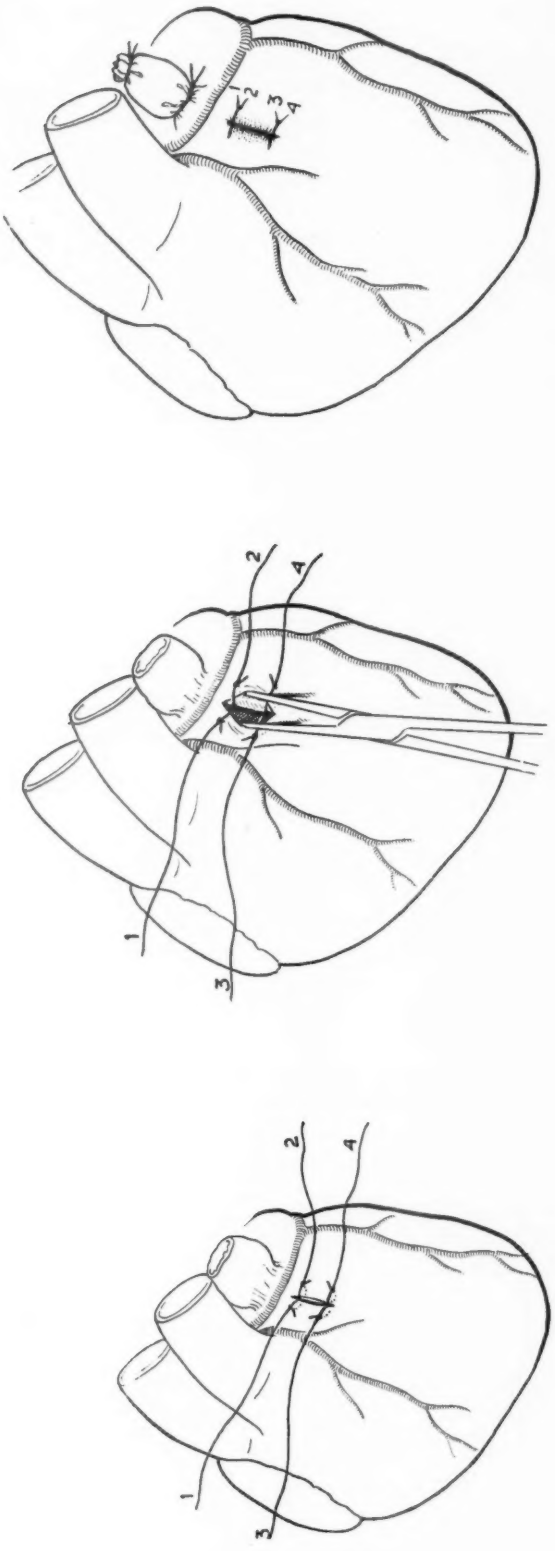
Mitral insufficiency was created in five dogs by excision of a portion of the lesser leaflet, by way of the auricular appendage. In two of these, a relatively bloodless field was obtained by temporary cardiac venous inflow occlusion, as described by Shaw and associates.[11] However, this was found to be less satisfactory than laceration of the mitral valve leaflets by a sharpened nerve hook, introduced by the left hand through the anterior wall of the left ventricle. The point of the nerve hook could be guided by and manipulated against the intracardiac finger, causing significant damage to the cusps, endocardium, and chordae (Fig. 2). This was augmented, in a few dogs with sufficiently large auricular appendages, by a second nerve hook passed from above along the intracardiac finger.

C.

B.

A.

Fig. 2.—*A*, Creation of mitral insufficiency; *B* and *C*, reconstruction of lesion found at autopsy, from auricular and ventricular exposures, respectively.



A. *B.* *C.*

Fig. 3.—Correction of mitral insufficiency. *A*, Imbricating sutures in place beside incision; *B*, cardiomyotomy; *C*, plication of annulus by sutures.

The nerve hook laceration technique was employed in the experiments that were assayed physiologically. Gentle compression over the site of introduction of the nerve hook, for hemostasis, was accompanied by disappearance of the jet; when pressure over this area was released, the jet reappeared, and showed no tendency to spontaneous correction. This observation provided a useful guide in placing the sutures.

Correction of Mitral Insufficiency.—The initial attempt to plicate the annulus consisted of placing one or two Lembert sutures immediately below the circumflex coronary artery, grasping liberal bites of left ventricular myocardium. This proved to be ineffectual, a finding that was subsequently corroborated in a recent report describing experimental attempts to produce infundibular pulmonic stenosis by a similar type of suture.[12] Efforts to create a tunnel by suturing auricle to ventricle over the circumflex artery were also disappointing.

The feasibility of excising a portion of left ventricular myocardium, to permit more effective plication, was brought out during a discussion with Dr. Robert Gross. The first method incorporating this principle employed two Lembert sutures parallel to the circumflex coronary artery and to each other. A vertical wedge of myocardium, extending for about two-thirds of the thickness of the ventricular wall, was excised under the loops of these sutures, and the sutures tied. The technique finally adopted is illustrated in Fig. 3. A superficial vertical incision was made in the epicardium at the site selected for plication, cephalad to the apex of the anterior papillary muscle. Two deep sutures of No. 0 black silk on curved Atraumatic needles were placed on each side of the incision. A fine curved clamp was employed to widen and deepen the incision for two-thirds to three-fourths of the estimated thickness of the wall of the ventricle, as in a Ramstedt procedure. The opposing sutures were tied over the defect. The intracardiac finger proved to be of no help in guiding these sutures.

The base of the auricular appendage was secured by tying the purse-string suture, and the free margins were tied over a Gelfoam pledget.* The pericardium was loosely approximated. Pericostal sutures were placed around the ribs above and below the divided intercostal space, and the thoracic musculature and skin were repaired with continuous silk sutures. Penicillin, 300,000 units, was administered intrapleurally at the conclusion of the operation, and intramuscularly for the first five days postoperatively. There were no dietary or exercise restrictions.

RESULTS

The production and elimination of a regurgitant jet were evaluated initially by palpation with the intracardiac finger. When the technique had become standardized, more precise evaluation by physiologic means was attempted. Electrocardiograms, intracardiac and intravascular pressure curves

*Supplied through the generosity of the Upjohn Company, Kalamazoo, Michigan.

Fig. 4.—Dog No. 26. Left ventricular and left auricular pressure curves. Representative pressure tracings. High v wave produced and corrected in auricular curves; no significant pressure changes.

Fig. 5.—Dog No. 21. Left ventricular and left auricular pressure curves. C wave changes in auricular curves, with little change in pressures.

Fig. 6.—Dog No. 27. Left ventricular and left auricular pressure curves. Extensive c wave and pressure changes in auricular tracings.

with strain gauge manometers, and at times phonocardiograms were simultaneously recorded* prior to creating the lesion, after producing the insufficiency, and following plication of the annulus. For these pressure tracings, relatively undistensible but flexible plastic tubing was attached to a Cournand needle in the left femoral artery, and to No. 22 gauge needles which were inserted into the pulmonary artery, left auricle, and left ventricle.

In the left auricular tracings the "a" wave represents auricular systole; the "c" wave coincides with the onset of ventricular contraction; and the "v" wave reflects filling of the auricle with blood from the veins when the mitral valve is closed. Mitral valvular insufficiency with consequent regurgitation should alter the configuration of the c and v waves.

Fig. 7.—Severe valvulitis and lacerations, twelve days postoperatively.

Detailed combined data have been obtained in twelve dogs with valvular lacerations. The remaining sixteen included the animals employed in the evolutionary phases of the investigation including the finger dilatations, as well as a few deaths due to anesthesia or technical mishaps. Following valvular laceration, significant alterations in the shape of the pressure curves and/or the absolute pressure values, comparable to those in the classical experiments of Wiggers and Feil,[13] were obtained in five dogs. The change illustrated in Fig. 4 is predominantly in the v waves, whereas in Figs. 5 and 6 the c waves are markedly altered. After plication of the annulus, the return of the tracings toward normal is evident in all three figures. This acute im-

*All the photographic tracings were taken with a multichannel electronic recorder, manufactured by Electronics for Medicine, Inc., New York.

provement has been maintained in pressure tracings in dogs sacrificed at intervals up to four months postoperatively. In all of these tracings the mean pressure has been integrated electronically. The elevation in end diastolic pressures reflects inaccurate leveling of the manometers with respect to the left auricle or ventricle.

In contrast to Figs. 4 and 5, marked changes in auricular pressures are noted in Fig. 6, with a considerable elevation following production of the jet, and a significant reduction after plication of the annulus. This is associated with the creation and correction of c wave alterations, with a v wave that appears unchanged. On the other hand, the v wave changes in Fig. 4 are accompanied by little in the way of pressure changes, and show a great deal of variation in height with different heart beats.

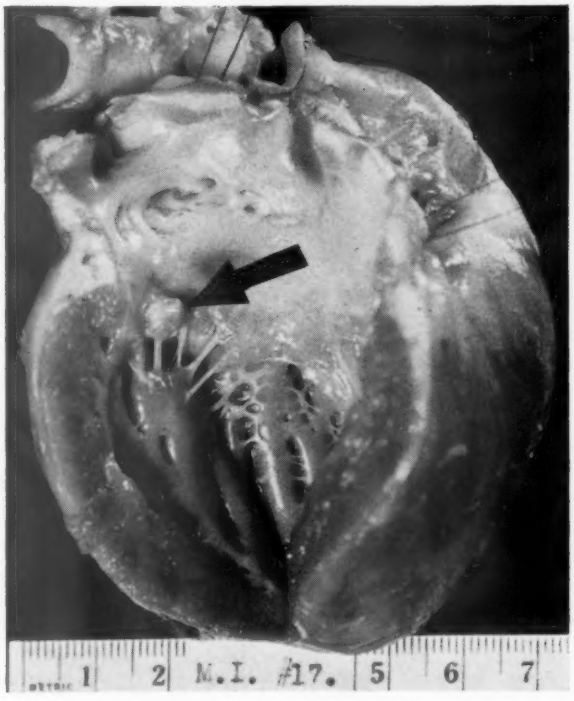


Fig. 8.—Fibrocalcific nodular healed valvulitis, thirty-three days postoperatively.

Definite changes in pressure tracings, such as those demonstrated previously, correlated well with the jet as palpated, and with autopsy demonstration of considerable valvular distortion. In one animal, however, the physiologic data showed only slight alterations, despite a strong jet felt at operation and extensive valvular lacerations with fibrinous valvulitis at post-mortem examination (Fig. 7). A partial explanation for this discrepancy may be found in the fact that the configuration of the intra-auricular pressure curve varies considerably as the position of the needle changes in relation to the valve orifice, as also does the sensation felt by the intracardiac finger. While this observation must modify complete reliance on pressure determinations

as an absolute reflection of grossly demonstrable lesions, it is true for the most part that minor changes in pressure tracings were associated with the production of less severe degrees of valvular damage, as noted in the remaining six dogs subjected to this analysis.

The electrocardiographic tracings recorded were all of standard limb Lead II. While changes in rate and rhythm were noted frequently during manipulation of the heart, there were no specific alterations suggesting myocardial or coronary arterial injury.

All the dogs that died postoperatively or were sacrificed were subjected to complete post-mortem examinations. Grossly demonstrable myocardial changes, indicating damage to the coronary circulation, were not encountered in any instance after the technique illustrated had been adopted. The areas included in the sutures at the myotomy sites were occupied by dense fibrous tissue, as observed in healing myocardial wounds by Thomas and Ziffren,[14] with no suggestion of aneurysmal dilatation. An actual bulge inward corresponding to the plication of the annulus could not be demonstrated.

There was considerable variation in the extent and location of valvular injury as found at autopsy. One or two small lacerations near the free margin of the lesser leaflet, and associated with little fibrinous reaction, constituted the group in which the trauma was considered slight. Even when extensive damage to the lesser leaflets had been inflicted, accompanied by lacerations in the aortic cusp, considerable fibrinous valvulitis, and subendocardial ecchymoses, the chordae tendineae showed almost no evidence of injury.

DISCUSSION

Many of the procedures currently being revived as experimental tools or clinical operations date back to the early part of this century. MacCallum[15] produced mitral insufficiency in 1906, by cutting the valve from above; Bernheim[16] sutured the leaflets to create stenosis, which he subsequently corrected by a cutting maneuver via the ventricle; and Cushing and Branch[17] and Scheppelman[18] introduced MacCallum's nerve hook into the left ventricle to cause regurgitation (Fig. 9), to cite only a few of the spectacular and neglected achievements of these and other workers of a previous generation. The bimanual technique utilized in the current investigation is a natural outgrowth of these earlier contributions, modified by the surgical procedures now in vogue in the treatment of mitral stenosis.

It is difficult to assay the significance of this traumatic mitral insufficiency in relation to its human rheumatic analogue. The wide spectrum of lesions contributing to the human disease makes it apparent that a single procedure probably will have a limited application at best. Mitral insufficiency secondary to shortening and fusion of chordae tendineae differs pathologically from loss of valve substance or great dilatation of the annulus, and commonly these and other lesions occur in combination in varying degrees. Much of the benefit

currently attributed to procedures designed to improve mitral insufficiency may in fact have been derived from the commissurotomy performed for the concomitant mitral stenosis.

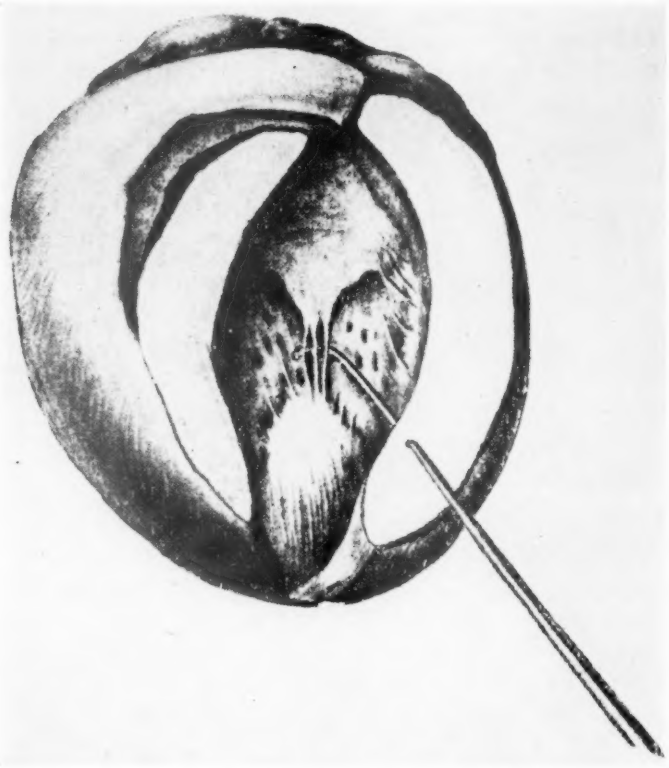


Fig. 9.—Division of chordae by MacCallum nerve hook, Scheppelman, 1912.[17]

The left auricular pressure curves with mitral insufficiency produced by valvular laceration are quite similar to those obtained by others[19] in cases of human rheumatic mitral insufficiency. A somewhat similar curve has been obtained in one case* at this hospital (Fig. 10), although it was not possible in this patient with a tense auricle and a diminutive auricular appendage for the operator to introduce his finger for palpation of the valve. In four instances of human rheumatic mitral insufficiency, in which the jet was corroborated by digital palpation, left auricular pressure curves similar to those in Fig. 11† were obtained, with absent a waves and c waves that merge into high v waves. The distensibility of the normal left auricles with normal low pressures in these dogs would tend to diminish regurgitant pressure changes. It is reasonable to expect, as demonstrated by Figs. 4 through 6, that changes in the shape of the curves would be more striking than increases in mean auricular pressures, and that the latter would be associated with the more extensive lesions.

*Exploration by Dr. Adrian Kantrowitz.
†Case of Dr. Allan Bloomberg.

In order to evaluate more accurately and completely the effects of experimentally produced mitral insufficiency, a study of auricular and ventricular volumes may be essential. The pressure-volume relationships in the normal auricle of the experimental animal before and after creating mitral insufficiency are hardly comparable to those in the tense, distended auricle of human mitral insufficiency. The fact that the shape of the auricular pressure curve may alter

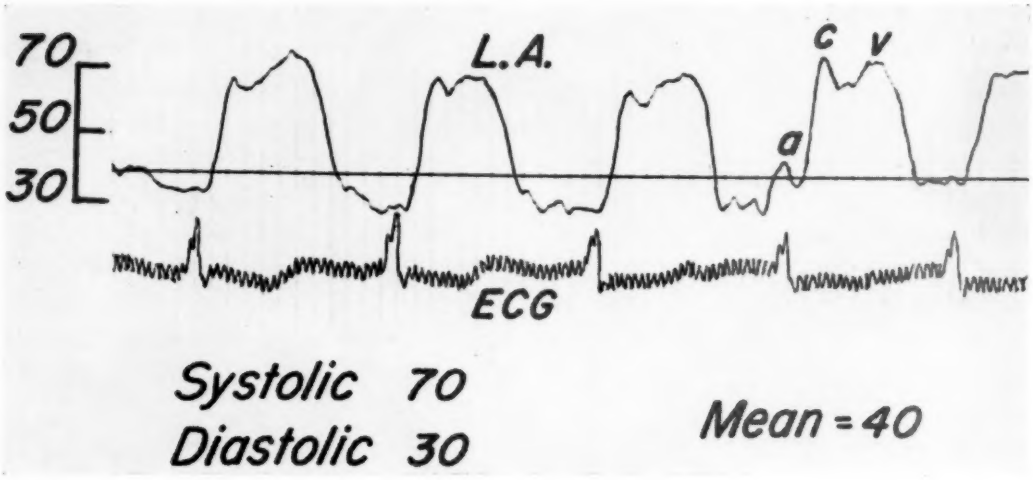


Fig. 10.—Left auricular pressure curve at surgery in human exploration (see text). High c and v waves.

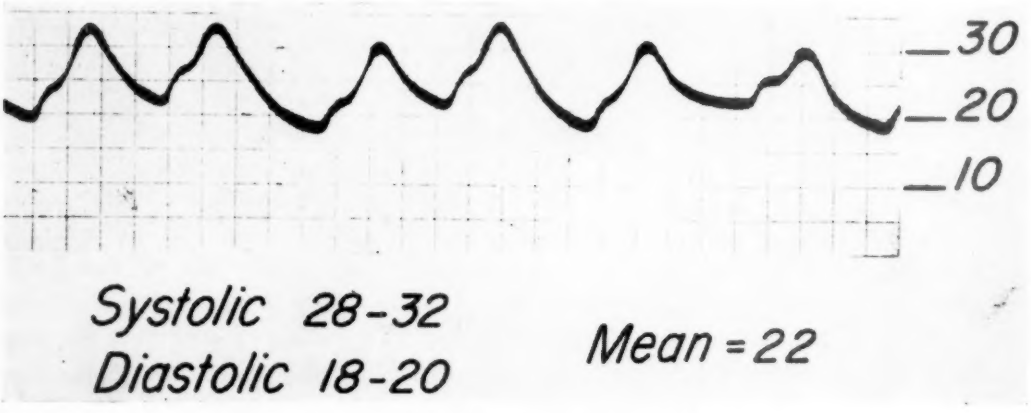


Fig. 11.—Left auricular pressure curve at surgery in case of human mitral insufficiency. Auricular fibrillation, with absent a waves, moderate c, and high v waves.

with changes in the position of the intra-auricular needle introduces an additional variable in this appraisal. The validity of an estimate of the presence and degree of a regurgitant jet by the intracardiac finger will be a function of the thoroughness with which the palpation is performed. As brought out in this study, it is possible to miss the jet, to estimate its intensity inaccurately, or to confuse it with a vibration of the cusps.

A relatively small valve defect, sufficient to cause a change in the c wave during the phase of isometric contraction of the ventricle, might be closed off

by the contraction of the annulus during actual systole, thus eliminating v wave alterations. This phenomenon illustrates the mechanism of the "plication" principle. The overlapping nature of leaflet approximation, as demonstrated in the mitral valve movie,[6] could also conceal or compensate for some of the valvular lesions found at autopsy.

Several dogs are being maintained for prolonged survival periods, with interim pressure recordings, to determine the ultimate effects of this procedure. The delayed development of mitral stenosis would constitute a significant drawback to clinical application of the method. To date this has not been observed, but the time elapsed is inadequate to permit such a conclusion. The demonstration of fibrocalcific nodules in the healing lesions (Fig. 8) suggests that the end result of the trauma alone, without the sutures, might be a valvular stenosis, and a few dogs are being followed in whom the lesion has been produced and left uncorrected.

One of the serious problems in mitral valvular surgery has been the incidence of postoperative embolization. It has been postulated that the obliterated orifice of the left auricular appendage might serve as the source of some of these emboli. The specimens illustrated in Figs. 7 and 8, photographed twelve and thirty-three days, respectively, after operation, show no evidence of a nidus for thrombosis or embolization on the endocardial aspect of the base of the auricular appendage. This has not been a consistent finding, however, and is the subject of further investigation.

In the course of these studies it is planned to observe directly the relation between intrapulmonary capillary "wedge" pressures and left auricular pressures in mitral insufficiency. An application of this plication principle to the correction of insufficiency of other valves is also in progress. A comparison of the valvular insufficiency obtained by partial cusp excision with that produced by valvular laceration will also be obtained.

Plication of the annulus has not been performed to date in a case of human mitral insufficiency. Since the evolution of the plication procedure, two of the patients explored for mitral stenosis demonstrated considerable regurgitation during operation. In neither instance was it possible significantly to alter the jet, as determined by the intracardiac finger or the auricular pressure curve, by compression at different sites superficial to the annulus, suggesting that the plication would be ineffectual. After adequate commissurotomy for the component of stenosis in one of these patients, the valve orifice was still held firmly open, deep in the ventricular chamber, at the apex of the valvular funnel. It is difficult to conceive of an appropriate procedure for the correction of such a deformity.

It is anticipated that patients will be encountered with mitral insufficiency in whom the valve ring is dilated and not calcified. In such a situation, if compression at different areas just below the circumflex coronary artery alters the regurgitant jet, plication of the annulus at one or more points is suggested as a corrective operation. This may be carried out alone, or in combination with other operative maneuvers, in the treatment of different forms of the valvular deformity.

SUMMARY

1. The anatomic position of the mitral annulus has been demonstrated by dissection studies to be slightly closer to the apex of the heart than is the circumflex coronary artery.

2. Traumatic mitral insufficiency has been produced in a series of dogs by valvular laceration.

3. Correction of the altered dynamics has been accomplished by plication of the annulus from the epicardial surface of the left ventricle, without compromising the coronary circulation.

4. Creation and elimination of the regurgitant jet has been documented by intracardiac palpation and pressure tracings.

5. The relationship between these results and the treatment of human rheumatic mitral insufficiency has been discussed.

We gratefully acknowledge the suggestions of Dr. Raymond E. Weston, Head of the Cardiovascular and Metabolic Research Service, Medical Division, Montefiore Hospital. Mr. Irwin Sternberg contributed invaluable assistance with the pressure recordings, and Mr. Alphonso Ivan Henry rendered considerable technical aid.

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REVASCULARIZATION OF THE HEART BY PEDICLED SKIN FLAP

An Experimental Study Investigating the Functions of Extracoronary Anastomoses

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UNTIL recently the treatment of coronary artery disease has been largely palliative. The success of this type of treatment is a tribute to Nature's resources in combatting occlusion of an end artery such as a coronary. Supportive treatment alone, however, results in the survival of only those in whom the vessel occluded is not sufficiently large to produce immediate death, or in whom a gradual narrowing of the arteries prior to the occlusion has stimulated a protective collateral blood supply. Unfortunately, many victims of this disease do not succeed in developing a sufficient number of collateral vessels to survive a massive occlusion, with the result that nearly one-half of all patients who have angina or who survive one coronary occlusion will die within two years of onset of symptoms.[1] On the other hand, recent advances in the early diagnosis of coronary disease may make possible the detection of the disease before any symptoms have become evident.[2, 3] This period of early coronary narrowing, when myocardial damage is least, is the opportune time to apply a method for revascularization if the method can be proved safe and useful beyond question.

We began an experimental study of the problem three years ago, utilizing a pedicled skin flap from the chest wall, in the hope that this method might bring an efficient collateral supply to the heart, and that by its use we might gain a clearer understanding of the means by which the heart may augment its blood supply.

Changes observed in the human heart following long-standing coronary insufficiency have suggested several of the approaches used by previous experimenters to supplement the coronary circulation. Prior to 1930, a number of writers reported autopsy findings of total occlusion of both coronary arteries which had apparently been compatible with life for a long time.[4-6] Dilated anastomotic channels were described between the systemic and coronary circulations which supplemented the inadequate coronary flow. Subsequently, injection studies of autopsy specimens revealed the more common means by which inadequate coronary flow may be supplemented.[7-9] These consist first of the development of anastomotic pathways between adjacent branches of coronary arteries, which by-pass areas of narrowing or occlusion.[1] The pathways are probably normally present but nonfunctional.

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Some excellent recent work, by two groups in particular, has resulted in a detailed description of the size and location of these anastomoses as they occur in autopsy specimens, and the relationship of various diseases to their appearance.[1, 10-13] A second possible mechanism for contributing added blood to a failing coronary supply was described by Gross[9] in 1921. It consists of an anastomosing network of small blood vessels which connect the systemic and coronary circulations, found around the root of the aorta, base of the pulmonary artery, and the pericardial reflections about the pulmonary veins and vena cavae. In the normal heart they are smaller than 30 microns in diameter. As a result of these observations several groups began studies of methods by which a rich systemic vascular bed might be made available to the coronary circulation. The premise on which these studies were based was that anastomoses between the coronary arteries and the immediately adjacent systemic vessels might carry sufficient blood to sustain the heart in the event of occlusion of a coronary artery. A second useful function of the anastomoses might be that the systemic vascular network would act as a bridge between one coronary tree and another, much as the intramyocardial anastomoses between coronaries have been found to function. Beck,[14] in 1935, published a method for accomplishing this by creating pericardial adhesions, joining the systemic vessels of the pericardium with the coronaries. In 1936 O'Shaughnessy[15] described the use of omentum for the same purpose. Subsequently, a large variety of tissues have been used as pedicled grafts to the surface of the heart, all with the purpose of bringing to the coronary arteries an available source of systemic blood vessels. Among the tissues used for this purpose have been pericardium,[16, 17] omentum,[15, 18] muscle flaps,[19, 20] mediastinal fat,[19, 20] lung,[21, 22] spleen,[23] stomach,[23] and bowel.[23]

In a similar way, another autopsy observation has suggested another avenue by which the coronary circulation might be aided. Cases with coronary insufficiency were noted in which dilated tortuous veins were found deep in the myocardium, presumably dilated Thebesian veins.[24, 25] These channels, described in detail by Wearn[26] in 1928, form a system of venous sinuses which connect the capillary bed of the myocardium with the ventricular cavity, and probably function as an auxiliary to the coronary sinus and anterior cardiac veins in returning venous coronary blood to the cavities of the heart.[26] Survival in these cases was attributed to a reversal in the direction of flow through the channels. The further observation that patients suffering from angina frequently lost their pain during an attack of right heart failure led Louis Gross[27] and others to reproduce the increased tension in the coronary sinus by surgical ligation of the vessel. Their purpose was to produce a widening of the intramyocardial collaterals as a result of elevated venous back pressure. This approach culminated in the reports by Beck and subsequent groups of introduction of arterial blood into the venous system of the heart, first by anastomosis of a systemic artery to the coronary sinus[28] and later by the creation of a fistula between the aorta and coronary sinus using a vein graft.[29]

Other surgical methods to treat coronary disease have included thyroidectomy to lessen the work load of the heart and thereby diminish its requirements for blood,[30] thoracic or pericoronary neurectomy to relieve the factor of coronary spasm,[31, 32] and implantation of a systemic artery directly into the myocardium.[33]

We have confined our attention to the possible effectiveness of the pedicled skin flap as a vehicle for the transport of systemic blood vessels to the heart. One of the few systemic vascular beds which has not previously been used is the subcutaneous blood supply. This avenue has several advantages. The first is simplicity of preparation and attachment. The preliminary stages of construction of the flap can be done under local anesthesia with little risk and the only major procedure would be the relatively simple operation of attaching the flap to the heart. Second is the ability of flaps to transport blood to avascular areas. Brown[34] has discussed the various situations in which a permanently pedicled blood-carrying flap is useful, and the salutory effect of a flap implanted into a region of radiation necrosis has long been known. The basic pathology of this lesion is a proliferative endarteritis with ischemic necrosis, and when a flap is implanted in the center of such an area the surrounding ischemic tissue increases in vascularity, a result of the growth into it of new blood vessels from the flap. Experimental studies of tubed flaps have shown that the ability of a flap to transport blood is a result of realignment of its vessels to correspond in direction with the long axis of the tube.[35] This ordinarily takes place in the first week and little further change is found before fourteen days.[36] By one month, however, histologic studies of flaps have shown a marked increase in the number of vessels in a flap, and studies of the functional capacity of tubed flaps indicate the vascular supply to be approximately 60 per cent of maximum at two weeks and 90 per cent of maximum at one month.[37, 38] If a tubed flap is then rendered ischemic by dividing and reimplanting one of its pedicles, the volume of blood carried by the other pedicle progressively increases, reaching a new maximum in approximately the same period of time as following the primary elevation.[39] By taxing a flap gradually, therefore, it can be made to carry progressively more blood, and attaching one end of a flap to an ischemic tissue produces the necessary stimulus. A pedicled skin flap attached to the heart offers its greatest advantages, however, as an experimental method to study the physiology of extracoronary anastomoses. Very little is really known about the direction of blood flow and the mechanical functions of extracoronary anastomoses. Most previous writers who have worked on this problem have had little difficulty in demonstrating at least some anastomoses with nearly every tissue used as a graft, but the direction of flow has been hypothesized from indirect evidence. Since all the vessels which enter a skin flap and form anastomoses with the coronary arteries must pass through its pedicle, the source of the blood vessels is isolated. Any extracoronary blood which reaches the myocardium passes through this pedicle, so that the volume and direction of flow through the anastomoses may be studied directly. From a physiologic

standpoint there is probably little difference between the function of extracoronary anastomoses formed with a skin flap and those formed with other tissues used for this purpose. The method, therefore, may help in understanding the physiologic functions of extracoronary anastomoses with any tissue.

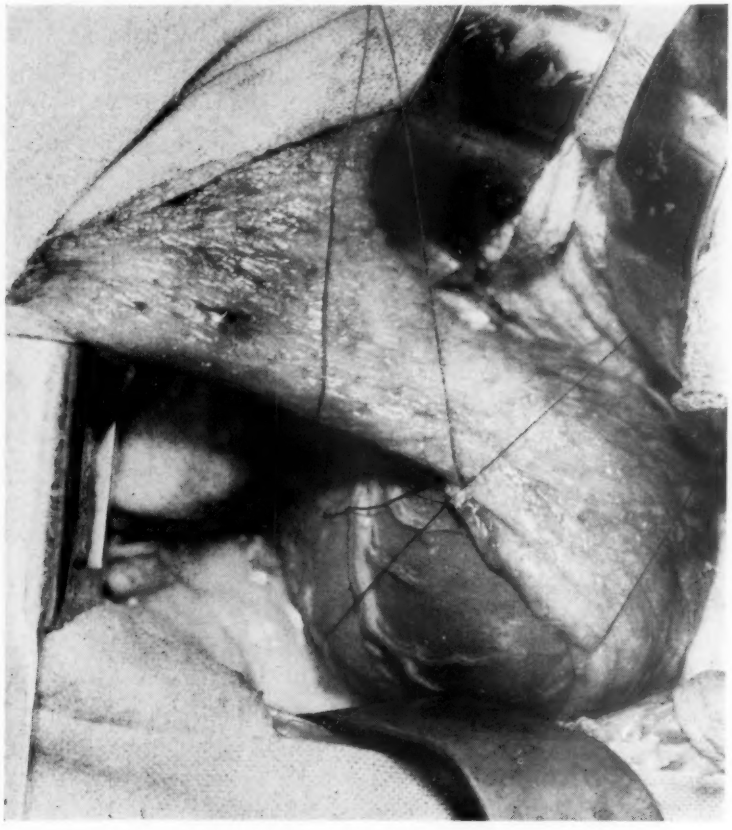
CONSTRUCTION OF THE PEDICLED SKIN FLAP

Our first objective was to find out whether it was possible to attach a flap to the heart and, if so, how high a mortality would result. In the early experiments a pedicled flap with its epidermis intact and with its proximal portion tubed was sutured directly to the ventricular myocardium.[40] The purpose of retaining the epidermis and tubing that portion which was not in contact with the heart was to provide a more valid experiment by excluding all sources of blood other than that which passed through the pedicle of the tube. Thirty-nine procedures were carried out in this manner and complications were less than 10 per cent. The usual complications were pericarditis or empyema and a few instances of pneumothorax from leaks of air around the base of the tube where it passed through the chest wall. None of these animals showed any evidence of constriction or mechanical interference with the function of the heart. The probable reason was that the heavy layer of fatty tissue which was transported with the skin flap, although it became adherent to the heart, was sufficiently elastic in consistency that its inner layer moved freely with the heart while the outer layer remained fixed by the skin of the flap. The fatty layer replaces the normal gliding surfaces of the pericardium and epicardium but maintains a continuity of tissue between the flap and myocardium in which blood vessels can travel. Although the epicardium was not abraded or chemically injured before the flap was attached, microscopic sections showed that the epicardium disappeared in the areas to which the flap was attached and electrocardiographic tracings showed progressive changes in the T waves which simulated pericarditis. Post-mortem studies explained the relatively low incidence of complications. When the animals were sacrificed it was found that the tube had become completely walled off from the free chest cavity by adherent lung, and that sinus tracts had developed along the tube from the pericardial cavity to the surface through which the secretions of the tube drained.

In order to avoid all possibility of infection from the secretions of the skin tube, we changed our method to include destruction of the secretory elements of the skin by removing the epidermis before implanting the flap. This does not diminish the volume of blood carried by the flap since most of the vessels lie in the dermis, and it insures per primum healing between the flap and the tissues through which it passes. One of the authors (C. G. N.) has used pedicled dermal-fat flaps such as this in human beings for the purpose of correcting large soft-tissue defects unassociated with loss of skin.[41] In these cases a tubed flap was prepared in the usual way, the outer layers of the epithelium were removed, and the flap was then buried beneath the skin, passing

the pedicle through a short incision in the skin of the recipient area. No infections or subcutaneous collections of secretions resulted.

The experimental technique we now use consists of first removing a split-thickness layer of skin thirty thousandths of an inch in thickness from the donor area for the flap using a Padgett dermatome. A flap approximately 10 by 16 cm. in diameter is then outlined within the area denuded by the dermatome, and located so that its pedicle overlies the third rib. The flap is elevated in a plane just superficial to the deep fascia so that all the subcutaneous tissue with its vessels is incorporated in the flap. A 3 cm. segment of



A.

Fig. 1.—Photographs taken while a denuded pedicled flap is attached to the heart. The flap has been passed through the major chest incision for illustrative purposes, rather than through a separate incision above. *A*, The flap is partially sutured to the heart and the remaining sutures have been placed but not tied down.

the third rib is removed and the flap, with its proximal portion tubed, is passed through the resulting defect into the thoracic cavity. The procedure within the chest is carried out through a separate incision at the fourth intercostal space, and after the pericardium is opened the flap is sutured directly over the myocardium, covering approximately two-thirds the total area of both ventricles. The pericardium and chest incisions are then closed, suturing the subcutaneous tissues firmly to the tube at the point where it passes through the chest wall. The skin heals solidly to the denuded base of the tube, and there has been no

evidence of any infection or irritation of the tissues through which the denuded flap passes. A few loose adhesions form between the lung and the tube before it enters the anterior mediastinum but no secretions or sinuses have been noted. We have used this technique in the past thirty-four consecutive animals and have had only one complication, a pneumothorax which resulted from inadequate removal of the epithelium of the tube in one of the early animals.

B.

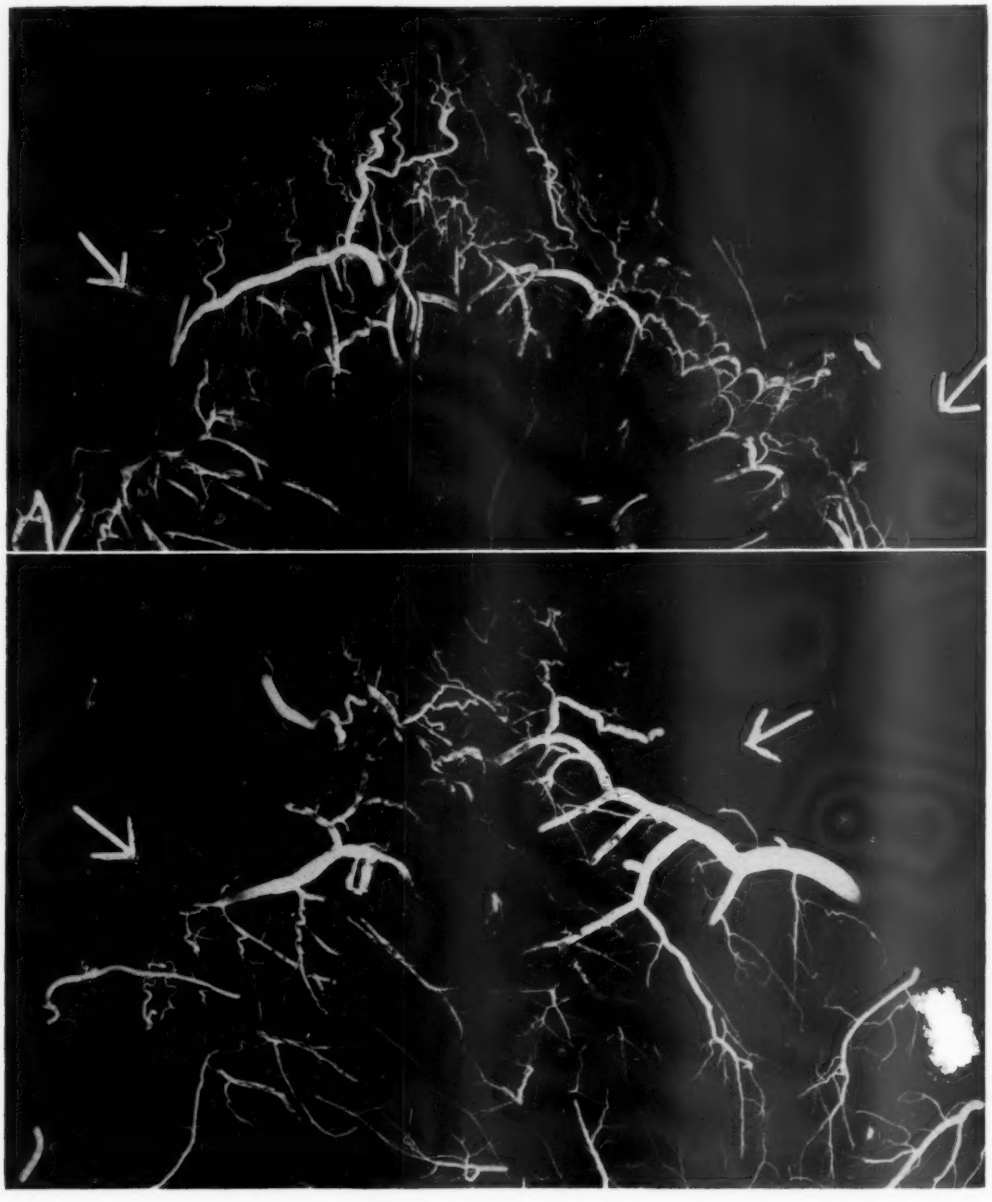
Fig. 1, *B.*—The flap is completely sutured to the heart, covering approximately two-thirds the total surface area of both ventricles.

THE DEVELOPMENT OF ANASTOMOSES BETWEEN FLAP AND HEART

Several methods were used to demonstrate the presence of anastomoses. In one of the early experiments a flap with its epidermis intact was attached to the heart, and one month later the pedicle of the flap was completely divided. Arterial blood spurted from both ends of the divided vessels and one week later, when the animal was sacrificed, the portion of the tube attached to the heart was found to be viable with good granulations on its cut surface. Since the tube was completely covered with intact epithelium the only source of blood to maintain its viability was through anastomoses in the area of the flap attached to the heart.

Another method consisted of cannulating the descending ramus of the left coronary artery in a specimen to which a flap had been attached for one month. A solution containing 35 per cent Diodrast and gentian violet was

A.



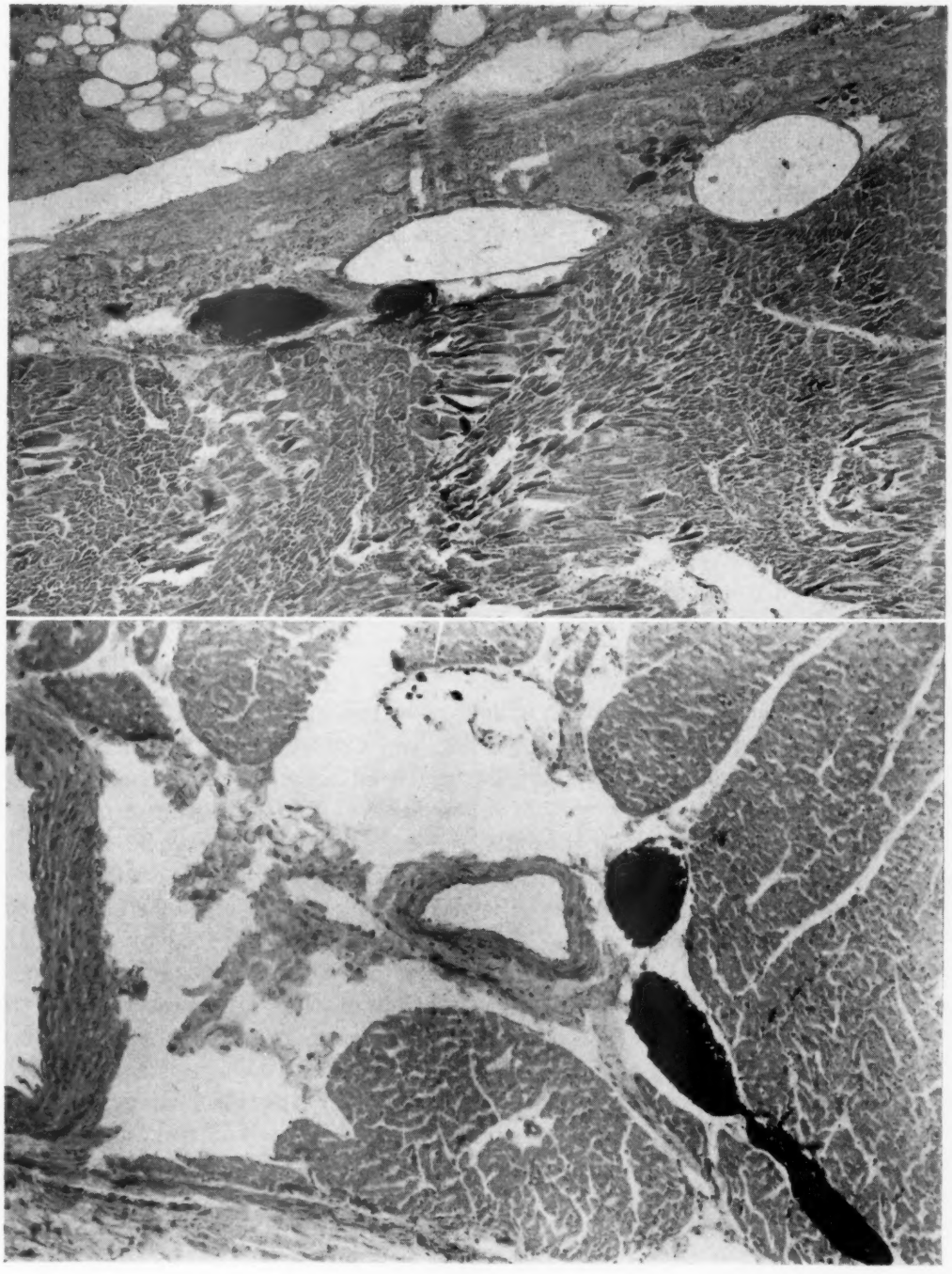
B.

Fig. 2.—X-ray films of transverse sections through the area of attachment of a flap to the myocardium in a specimen injected with bismuth through the arteries of the flap. The arrows indicate the borders of the flap. Vessels located above the level of the arrows lie in the flap, while those located below are in the myocardium.

A, Numerous arterioles from the flap extending down into the myocardium.

B, The prominent vessel on the right is a major coronary artery. A large arteriole can be seen extending from it into the flap.

A.



B.

Fig. 3.—Microphotographs of the myocardium of specimens injected through the vessels of the flap with bismuth oxychloride. *A,* A specimen which was injected through the arterial system of the flap. The arteries in the myocardium have filled with bismuth but two large veins can be seen which are devoid of injection medium.

B, A specimen which was injected through the venous system of the flap. A coronary artery can be seen which does not contain bismuth while the veins are filled.

injected at a pressure of 70 mm. mercury. The colored dye appeared at the transected end of the pedicle and x-ray films demonstrated the presence of radiopaque media within the vessels of the tube.

A final method, which has been described in detail in previous communications,[40, 42] consisted of injecting through the vessels of the tube a 20 per cent aqueous suspension of bismuth oxychloride at a pressure of 220 mm. Hg. This radiopaque media has a particle size which is too large to enter the capillaries and which will not pass through arterioles smaller than 35 or 40 microns in diameter. The medium filled the entire coronary system of the heart (see Fig. 2), and since all of it came from the vessels of the flap the anastomoses were demonstrated to be at least arteriolar in caliber. Microscopic examination of the myocardium in specimens injected in this manner revealed bismuth only in the arterial tree of the heart. Because the medium could not pass through the capillary barrier, only the arteries in the flap filled with bismuth and it entered only arteries in the heart. In other specimens, injected through the venous system of the flap, bismuth was found to have filled only the venous system of the myocardium (see Fig. 3). It seems clear that when anastomoses form between the coronary and systemic vessels, the systemic arteries anastomose only with coronary arteries and the systemic veins anastomose only with coronary veins.

WAYS TO STUDY USEFULNESS OF ANASTOMOSES

We had at this stage demonstrated that a pedicled skin flap could be attached to the heart in dogs with a low resulting mortality. It had been determined that arteriolar anastomoses between the coronary arteries and the systemic vessels of a skin flap develop much as previous experimenters have found them with systemic vessels of other tissues. The remaining problem was how best to study the usefulness of extracoronary anastomoses, should they be produced in a human being with coronary disease. Previous writers have ligated coronary arteries, usually the descending ramus of the left coronary artery, at specific intervals after the heart has been protected by one of the methods described. A decrease in the mortality from coronary ligation in protected animals as compared with ligation of the same vessel in control animals has been accepted as indicating the value of the method. Several objections can be raised to this conclusion. First of all there is a wide variation in the anatomic arrangement of the coronary arteries in dogs, and consequently an unpredictable effect from ligation of a specific artery in a specific animal. For statistically valid results, therefore, a very large series must be used. Furthermore, for an accurate study the ligation must take place at exactly the same site in every animal included in the series. The site chosen has usually been the origin of the descending ramus, and ligation even a few millimeters further down will allow escape of some of the proximal branches and considerably alter the mortality rate. Ligation at this point in a control animal is no problem, but exact ligation at this same point in an area filled with scar tissue and adhesions from a previous operative procedure is another matter. The result is that animals whose hearts have been protected by one of the surgical methods have a greater chance of inaccurate ligation than

the control animals and consequently a greater chance of survival. It occurred to us also that side effects of which we were unaware might be produced by the surgical method used, and might cause the decrease in mortality for which the method was credited. For these reasons a more direct study of the functions of the extracoronary anastomoses seemed indicated, and the pedicled skin flap appeared a useful means to this end.

The central coronary blood pressure in a normal heart is approximately the same as aortic pressure.[43] If anastomoses form between the coronary vessels and the systemic vessels of a tissue attached to a normal heart, therefore, it seems unlikely that blood will flow through the anastomoses toward the heart without a favorable pressure gradient. This is probably not the situation in a human heart whose coronaries have been narrowed and partially occluded by sclerosive disease, and here the direction of flow might well be toward the heart. At least two new experimental methods had to be developed, therefore, in order to carry the study further. One necessity was to find a way to simulate in the experimental animal the disease we wished to treat in the human being. The other was to find a direct method for demonstrating the direction of blood flow through the anastomoses.

A METHOD FOR REDUCING CORONARY FLOW

Since it was not practicable to induce coronary arteriosclerosis in the experimental animal, a mechanical method had to be devised which would first produce myocardial ischemia and eventually complete occlusion of an artery. Sudden occlusion with no preliminary ischemia ignores the diffuse vascular damage which is common in the human disease, and results in infarction with no opportunity for preliminary vascularization. The method should not require a second operation for its execution, first because of the difficulties in isolating the correct site for occlusion when reoperating in an area distorted from a previous operation, and second because the addition of the trauma of a surgical procedure to the shock of a coronary occlusion will considerably increase the mortality.

A number of methods were explored. These included the use of silk snares placed around the coronary arteries and led out to the skin through polythene tubing, wrapping the coronary arteries in reactive polythene, injecting the adventitia of the artery with dicetyl phosphate and then encasing the vessel in a metal cuff, and burying radon seeds of varying strengths adjacent to the wall of a coronary artery in the hope of stimulating the formation of a thrombus. These have been discussed in detail in a previous communication.[44] Briefly, we found that most of them were occasionally successful but none reliable. The one consistently successful method we have found is the use of a stainless steel clip which is closed by a spring and which is held open by a wedge of catgut when the clip is placed around a coronary artery. As the catgut is absorbed, the clip slowly closes, eventually producing complete occlusion of the artery (see Fig. 4). The clip is made from a stainless steel molybdenum alloy, type No. 316, No. 22 gauge wire (Brown and Sharpe), 0.025 inch diameter, and hard tempered. This alloy is completely nonreactive in the tissues. There are eight coils in the spring which allows sufficient elasticity to open the clip fully for

placing around a coronary artery and produces a tension in the fully closed position of approximately 100 Gm. When the clip is placed around a coronary artery it is held open by catgut which is wrapped around the lower jaw so that the clip closes only far enough to hold it around the vessel but not far enough to produce occlusion. The time of closure may be varied by using different grades of catgut. Plain catgut 00, which we have used, produced occlusion

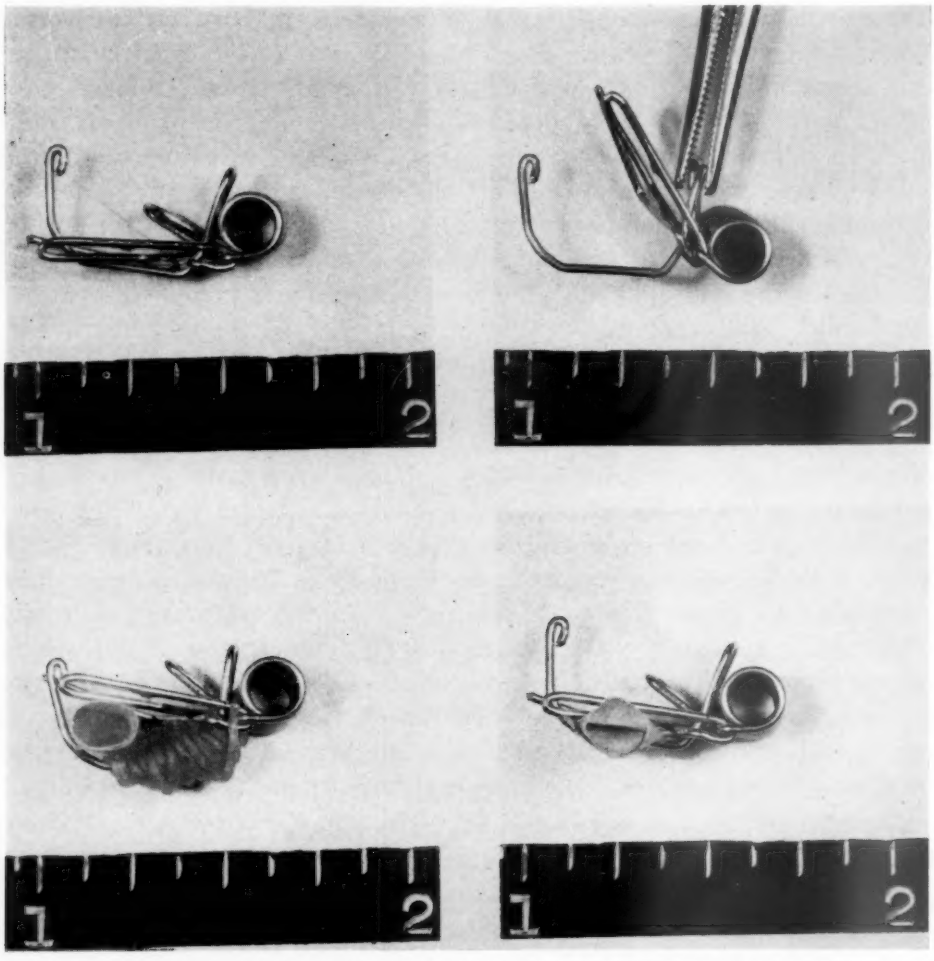


Fig. 4.—Stainless steel clip used for slowly occluding coronary arteries without reoperation. The upper two views show the clip completely closed (*left*), and held open by a clamp in position to be placed around a coronary artery (*right*). In the lower two views a roll of paper has been used to simulate a coronary artery. At the lower left the clip has been placed around the vessel but is prevented from closing by a wedge of catgut wrapped around the lower shaft. At the lower right the catgut has absorbed and the clip has closed, completely obliterating the lumen of the vessel.

in eight weeks in all the animals studied. The exact time of complete closure is unpredictable, however, since the catgut varies considerably in speed of absorption, and the vascularity of the bed in which the catgut is placed affects its rate of disappearance. We have placed clips of this design around a total of twenty-seven coronary arteries and only two have failed to produce complete occlusion of the vessel. The failures resulted from defective clips.

This method by no means accurately reproduces coronary disease as it occurs in human beings. It does not produce the diffuse narrowing and ischemia from damage to the smaller arteries which is seen in the human disease, nor does it superimpose on an ischemic heart the final blow of a sudden complete occlusion, but it does arrest arterial flow gradually through the normal channels without the insults of anesthesia and operation, and for this purpose forms a useful tool in the experimental study of methods of treatment.

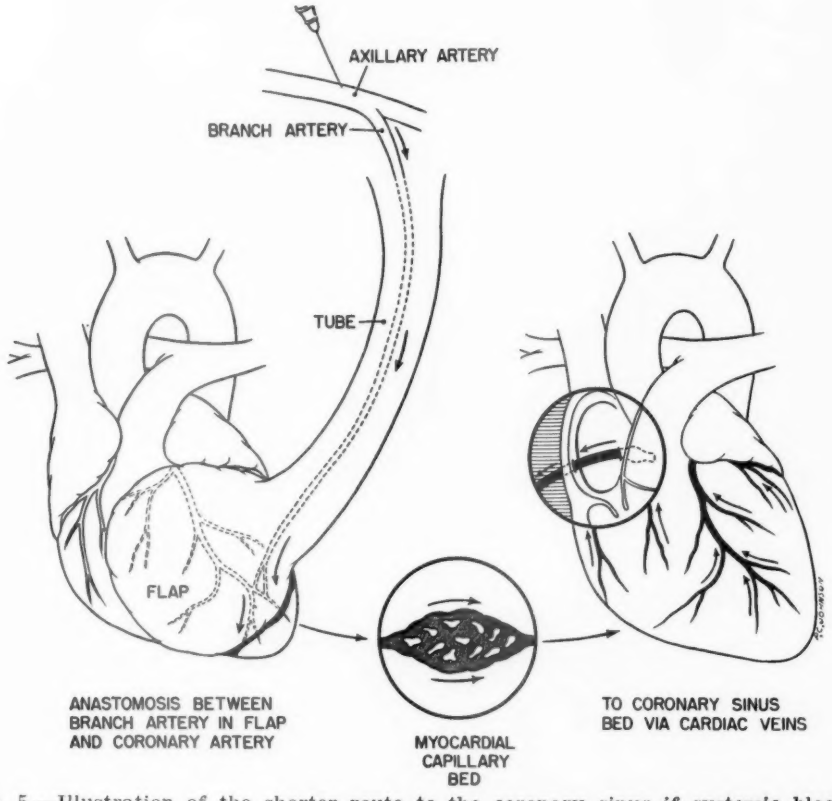


Fig. 5.—Illustration of the shorter route to the coronary sinus if systemic blood passes through anastomoses into the coronary arteries. A dye injected into the axillary artery above the branches which supply the flap may reach the coronary sinus by two routes. Either it may take the normal course through the systemic and pulmonary circulations and finally enter the coronary arteries; or it may take the route illustrated, passing down the vessels of the flap, through the anastomoses with the coronary arteries, through the myocardial capillary bed, and into the coronary sinus.

A METHOD FOR STUDYING DIRECTION OF BLOOD FLOW THROUGH EXTRACORONARY ANASTOMOSES

Since all the vessels supplying a flap pass through its pedicle, several methods are available for studying directly the function of the anastomoses. If an animal with a pedicled flap protecting its heart survived coronary occlusions and if subsequent ligation of the pedicle resulted in the death of the dog, it would be difficult to escape the conclusion that the flap was responsible for the earlier survival. Failure of the animal to die following this procedure would suggest that blood flow through the vessels of the pedicle probably was not responsible for the initial survival. It would not indicate whether function of

the flap as a bridge between the coronaries affected survival since the vessels of the flap might continue this function even with the pedicle ligated. Dissection of the flap from the surface of the heart, however, would be a method for destroying this function of the flap. These procedures are simple and they serve as useful checks against the dye injection method to be described.

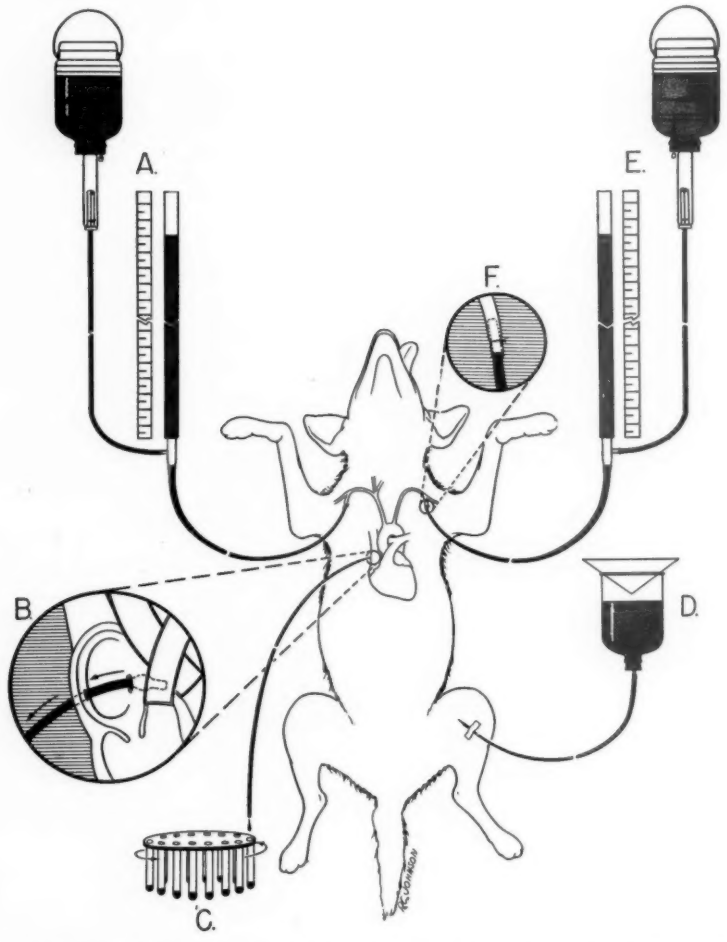


Fig. 6.—Experimental technique used to demonstrate in the living animal the direction of blood flow through extracoronary anastomoses with vessels of the skin flap.

F, Cannulas tied into both internal mammary arteries so that fluids injected through them enter axillary arteries but the cannulas do not interfere with blood flow through the axillary arteries. A continuous saline flow is maintained between injections to keep cannulas patent.

A and *E*, Saline manometers connected into the system for continuous record of systemic blood pressure.

B, Catheter placed in coronary sinus to carry myocardial venous blood to collecting device. The catheter is passed into the right atrium through a purse-string suture in the atrial wall and then easily guided into the coronary sinus.

C, Collecting device similar to that described by Newman and associates.[45] Total coronary sinus output is collected in three-second samples during the test.

D, Open transfusion flask with cannula in peripheral vein for returning coronary sinus output to the circulation between tests.

The idea for this method was first suggested to us by Dr. George P. Robb. It is based on the belief that if the blood traveling along the vessels of the flap passes through the anastomoses with the coronary arteries, it will reach the myocardium earlier than the same blood traveling the normal route. Most of

the vessels which supply the flap are branches of the left axillary artery. If a dye is injected into the left axillary artery above these branches there are two possible routes by which it may reach the myocardium. The normal route is down the arm, through the systemic capillaries, back to the right heart by the axillary vein and superior vena cava, through the entire pulmonary system to the left heart, and then through the coronary arteries to the myocardium and eventually the coronary sinus. By this route the dye takes approximately thirty seconds to reach the coronary sinus. The other possible route might be thought of as a short circuit through the vessels of the flap. Here the dye after injection into the axillary artery would pass into the arteries of the flap, through the anastomoses with the coronary arteries, and then into the myocardial bed and the coronary sinus. Dye injected into a

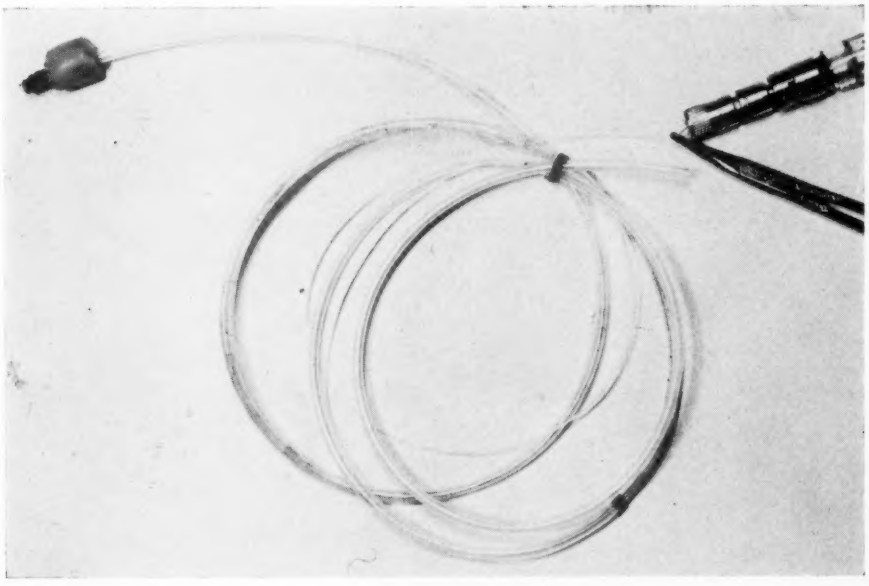


Fig. 7.—Catheter used for conducting blood from the coronary sinus to the collecting device. The catheter is a double lumen tube with a half-inch diameter balloon connected to the smaller lumen. After the catheter has been inserted through the orifice of the coronary sinus the balloon is inflated, which serves the double purpose of maintaining the position of the catheter in the coronary sinus, and preventing contamination of the coronary sinus blood by retrograde flow from the right atrium.

coronary artery reaches the coronary sinus in nine seconds, so that if the direction of blood flow through the anastomoses is toward the heart, the dye traveling through the vessels of the flap should reach the coronary sinus before the dye traveling the normal route. The techniques used are illustrated in Fig. 6. Cannulas are first tied into the origins of the internal mammary arteries on both sides so that injected fluids enter the axillary artery but the cannula does not interfere with normal flow through the vessel. Two different dyes are simultaneously injected through the cannulas, temporarily occluding the axillary arteries proximal to the injection to prevent retrograde flow of the dye. Since the branches of the right axillary artery do not connect with the vessels of the flap, the dye injected into this artery serves as a control to measure the normal circulation time to the coronary sinus. Some of the dye

injected into the left axillary artery takes the normal course but some of it may take the short circuit through the flap, and the time of its appearance in the coronary sinus is compared with the time required for appearance of the control dye. Beginning at the time of injection, the entire coronary sinus output is collected at three-second intervals, using the catheter illustrated in Fig. 7 to remove the blood from the coronary sinus and distribute it into collecting tubes. The collection device is similar to that described by Newman and associates[45] and consists of a disk with collecting funnels arranged at equal distances around the periphery, rotating at a fixed speed so that the total blood flow is divided into consecutive samples which are collected every three seconds. The heparinized samples are then centrifuged, the plasma is pipetted into 0.5 ml. micro cuvettes, and the content of each dye in the respective samples is read in a spectrophotometer. The two dyes employed are Evans blue and brilliant vital red. One cubic centimeter of each dye is injected, using a 2½ per cent solution of Evans blue and a 5 per cent solution of brilliant vital red. Both are protein bound dyes and are similar in pharmacologic properties. They are sufficiently far apart in the spectrum so that the presence of one interferes little with accurate reading of the other, and this error can be corrected by preliminary graphs of the degree of interference caused by one dye at the wave length of the other. The values for the two dyes are then plotted on the same graph.

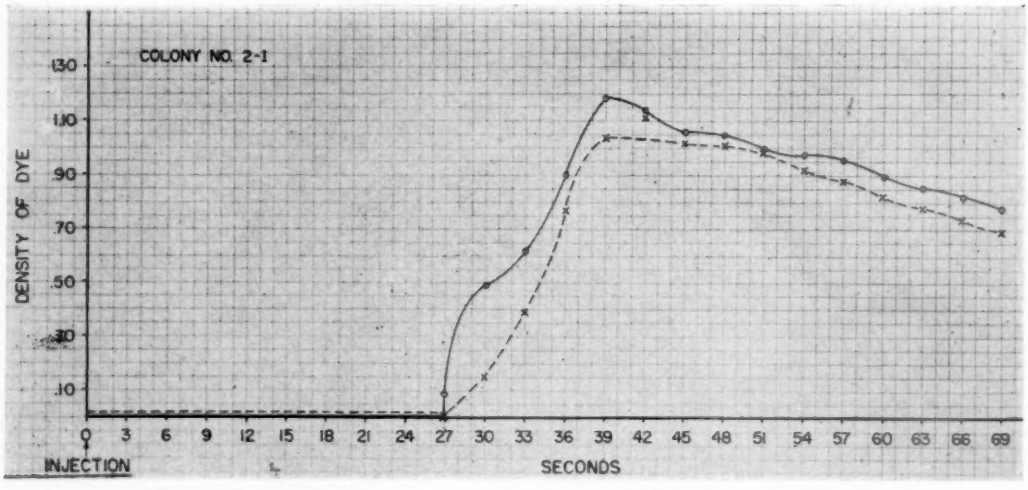


Fig. 8.—Typical study using the dye injection method described, in an animal protected by a flap and with complete occlusion of the circumflex and descending rami of the left coronary artery. The dotted line represents the dye injected into the left axillary artery. The solid line is the control dye simultaneously injected into the right axillary artery. The study suggests that blood was not flowing through the anastomoses toward the heart. This animal survived subsequent ligation of the pedicle of the flap with no changes in the electrocardiogram. We later demonstrated that animals can survive this degree of slow occlusion without artificially induced anastomoses.

A typical study is illustrated in Fig. 8. The dyes follow identical curves and there is no indication of an early rise in the dye injected into the left axillary artery. We feel that in this animal the study indicated that blood was not flowing from the flap toward the heart.

RESULTS

Using these methods, eight dogs were set up with their hearts protected by denuded flaps and with self-closing clips placed around the origins of the descending and circumflex rami of the left coronary artery. One of these animals died seven weeks later and autopsy revealed complete occlusion of both the vessels around which the clips had been placed and a large left ventricular infarct. The seven remaining animals all survived. Four of these were sacrificed at ten weeks and all except one had complete occlusion of both vessels and no infarct. The one exception had complete occlusion of the descendens but only 70 per cent occlusion of the circumflex, a result of a defective clip. The remaining three animals were presumed also to have had complete occlusion of the descending and circumflex rami and to have survived, and these three were operated upon at twelve weeks and clips placed about their right coronary arteries at origin. All three survived, and eight weeks later, when they were sacrificed, two were found to have had complete occlusion of the right coronary artery and complete occlusion of all branches of the left except the septal. The third had complete occlusion of the circumflex and right coronary but partial occlusion of the descending. This represents occlusion of approximately 80 per cent of the total cross-sectional area of the coronary arteries, yet all the animals appeared healthy and none showed evidence of infarction.

Using four control animals, clips were placed about the descending and circumflex rami at origin and no other procedures were carried out, although a few postoperative pericardial adhesions were inevitable. One of the controls died at two weeks with complete occlusion of the descendens but a patent circumflex. The remaining controls survived, and when they were sacrificed at eight weeks all of them were found to have complete occlusion of both branches and no infarct.

Dye injection studies, described earlier in this paper, were carried out in all animals surviving coronary occlusions and protected by flaps. No animal showed evidence of blood flow through the anastomoses toward the heart by this method. These results were strengthened when ligation of the pedicle of the flap in animals surviving coronary occlusion failed to produce a fatality and resulted in no change in the electrocardiographic tracing.

The flap was dissected away from its attachment to the heart in one animal who had complete occlusion of the descending and partial occlusion of the circumflex. This procedure resulted in changes in the electrocardiogram typical of a current of injury (see Fig. 9). Ninety minutes later, however, the tracing had returned to normal and the animal died after another two hours from exsanguination.

Perfusion studies of the coronary anatomy were then carried out in heart specimens removed from both the control animals and those protected by flaps. A 20 per cent suspension of bismuth oxychloride in saline solution was used, and the injections were carried out through various coronary arteries at pressures of 150 mm. Hg. Injection of this suspension into a coronary artery in a normal heart will result in the filling of only that vessel, and the other

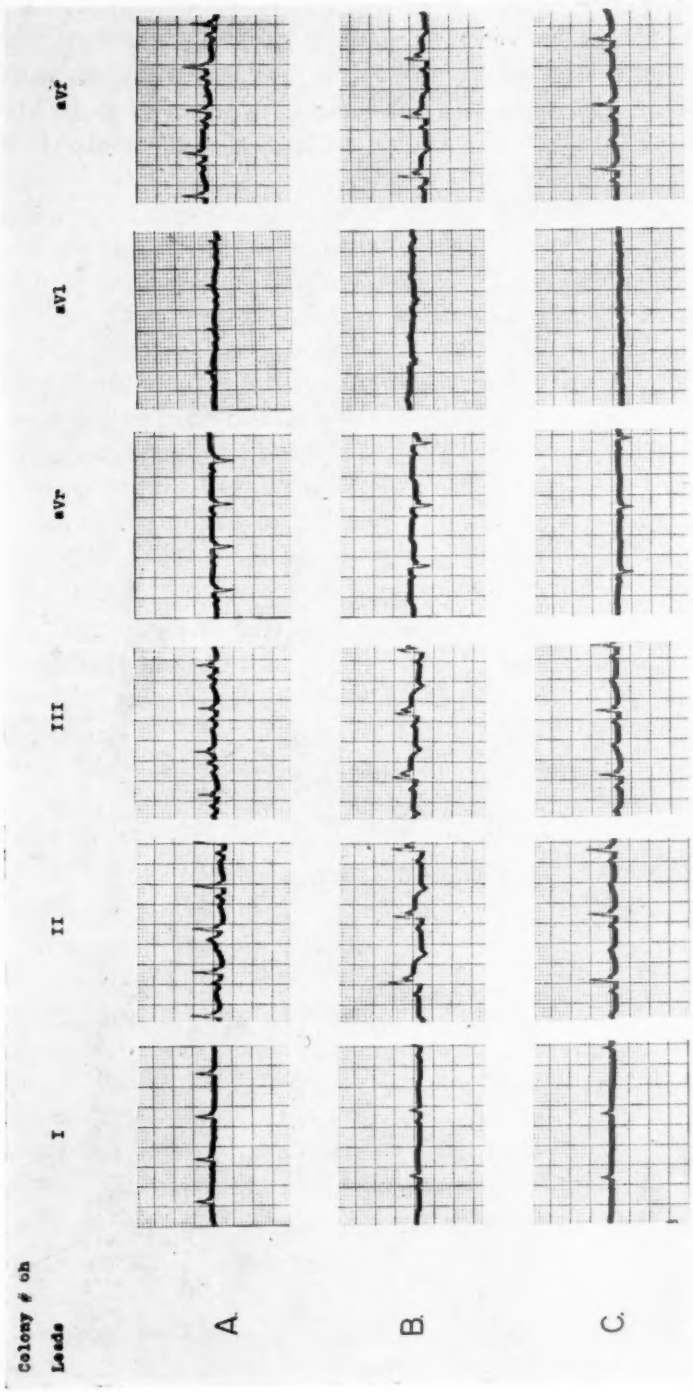
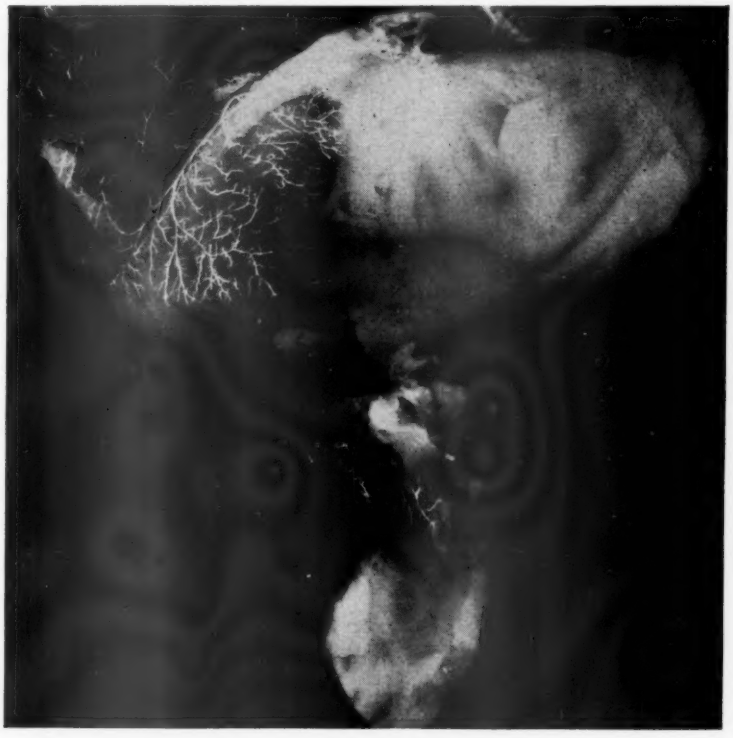


Fig. 9.—Electrocardiogram of an animal with complete occlusion of the descending ramus and protected by a flap. *A*, Taken after entering the chest. The tracing is normal for this dog. *B*, One-half hour later, after the flap had been dissected away from its attachment to the heart. The tracing is typical of a current of injury. *C*, Two hours later. The tracing has returned nearly to normal, with no remaining evidences of ischemia.

coronary arteries will be free of injection material since the anastomoses between the coronary arteries are normally too small to permit passage of the media (see Fig. 10, *A*).



A.

Fig. 10.—X-ray films demonstrating the development of intercoronary anastomoses following slow coronary occlusion. Both specimens were injected through the right coronary artery with a 20 per cent suspension of bismuth oxychloride, and the hearts have been opened and unrolled so that the right ventricle lies at the extreme left, the septum at the extreme right (in *A* the septum has been detached and is seen below), and the left ventricle in the center.

A, Normal heart. Only the right coronary tree has filled with bismuth. No anastomoses larger than 40 microns are present.

The results were somewhat variable, perhaps because of differences in technique. In the three control animals the injection was carried out through the right coronary artery which was patent, and resulted in filling of the occluded descending and circumflex rami in two of them, indicating the presence of large anastomoses between the occluded and nonoccluded arteries (see Fig. 10, *B*). Animals protected by flaps and with occlusion of the descending and circumflex rami were injected through the right coronary also. X-ray films of these specimens showed good filling of both occluded branches of the left coronary and also some bismuth in the vessels of the flap, indicating that some of the bismuth reaching the left coronary artery may have used the vessels of the flap as a bridge.

The animals with flaps attached to their hearts which had survived occlusion of all vessels except the septal were injected through the septal. This

resulted in partial filling of the other coronary arteries, indicating the existence of intramyocardial anastomoses between the septal and the other coronary arteries. In this instance the flap could not have acted as a bridge since it is at no point in proximity with the septal.

B.

Fig. 10, *B.*—Specimen from a control animal in whom complete occlusion of the descending and circumflex rami had been produced by the method described earlier. No flap was attached to this heart. Injection through the right coronary alone filled all the coronary vessels, indicating the existence of large intramyocardial anastomoses between the coronary arteries. Note the presence of bismuth in the vessels of the pericardium (above).

DISCUSSION

Some authors using surgical methods to treat coronary disease have hastened, in their enthusiasm, to apply the method to human patients with minimal experimental justification. It is entirely possible that methods which cannot experimentally be proved useful still may be of value in the human being with coronary artery disease. Nevertheless, we feel that all reasonable avenues for experimentally studying the surgical method should be exhausted before it is applied to human beings. The present studies emphasize the caution required in interpreting survival following coronary occlusion.

It seems obvious that when the coronary arteries were occluded slowly in these dogs, the animals were capable of protecting the blood supply to their hearts without the aid of outside sources of systemic blood. This was probably accomplished by the development of large intercoronary anastomoses, much as occurs in the human being with coronary disease. It also seems clear that

with slow occlusion of three of the four major coronary vessels, blood did not flow through the anastomoses from the flap toward the heart. This by no means establishes either the value or lack of value of extracoronary anastomoses. It merely indicates that the degree of occlusion we have so far produced by the slowly closing clips is insufficient to tax the heart beyond its normal ability to protect itself, and we have therefore not yet simulated the human disease where death supervenes. We believe that the function of the extracoronary anastomoses cannot be adequately tested until the method for occlusion overtaxes the heart's usual protective mechanisms and consistently results in death of control animals.

The dynamics of blood flow through the coronary arteries is quite different from that in the systemic vessels. In contrast to the systemic flow, blood flow through the coronary arteries occurs largely during diastole and the flow stops almost completely when the coronary blood pressure is at its peak.[43] The reason is obvious when it is considered that most of the peripheral branches of the coronary arteries are embedded in the muscle of the heart, and that contraction of the myocardium compresses these vessels and raises peripheral resistance to the point where flow is diminished. Blood flow into the coronary arteries through extracoronary anastomoses, therefore, must also take place during the period of myocardial relaxation. This is the period of lowest systemic blood pressure, although retardation of the peripheral pulse peak, as suggested by Kantrowitz,[46] may raise this pressure. It is conceivable that systemic diastolic pressure may not be high enough to force blood into the coronary system during the period of myocardial relaxation, even when the coronary orifices are occluded, and it is also possible that myocardial contraction may force systemic blood back out through the anastomoses. If this is the case, none of the methods for creating extracoronary systemic anastomoses are of value. We feel it is most important to find out whether flow can ever take place toward the heart through extracoronary anastomoses, regardless of the experimental conditions required to bring this about, for demonstration of flow in this direction assures a possibility that the anastomoses are of value. Toward this end we are continuing these studies by occluding more of the coronary orifices, until we can regularly produce death in the control animal or discover the reason for survival.

SUMMARY

Three experimental methods are described which may be used to study the functions of extracoronary anastomoses produced in the laboratory animal.

The first is the choice of a pedicled skin flap as the vehicle to bring systemic blood vessels to the surface of the heart. Extracoronary anastomoses formed with the vessels of this tissue are more easily studied than those formed with other tissues, and the procedure is simple to carry out.

The second is a way to produce slow complete occlusion of a coronary artery without reoperation. This is accomplished by the use of a stainless steel clip which is closed by a spring and is held open by catgut which slowly absorbs after the clip is placed in the tissues.

The third is a technique for determining the direction of blood flow through extracoronary anastomoses in the living animal, and it consists of a comparison of the times required for blood to reach the coronary sinus by the normal route and by a shorter route through the anastomoses.

Using these methods we have occluded up to 80 per cent of the coronary arterial supply in animals protected by flaps, and present evidence suggests that the extracoronary source of blood was not responsible for their survival. The findings neither prove nor disprove the value of extracoronary anastomoses, but merely indicate the extent to which the normal heart is capable of protecting its blood supply, following slow occlusion. This method of occlusion requires nearly total coronary artery closure before simulating coronary disease in the human being, and further studies in this direction are being carried out.

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A METHOD OF MAINTAINING ADEQUATE BLOOD FLOW THROUGH THE THORACIC AORTA WHILE INSERTING AN AORTA GRAFT TO REPLACE AN AORTIC ANEURYSM

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THE usefulness of aorta homografts in the treatment of coaretation of the aorta has been amply demonstrated. Their employment in replacing segments of aorta injured by disease would seem a natural sequence. The collateral circulation which is present in coaretation makes it possible to clamp the aorta for long periods of time while the graft is sutured in place. When dealing with nonobstructive lesions, however, the aorta may not be occluded with impunity. The period of occlusion of the thoracic aorta required to produce varying degrees of paraplegia in the dog often does not exceed fifteen minutes.[1] At one time Crafoord[2] suggested routine occlusion of the aorta in the closure of patent ductus arteriosus in patients and stated that paraplegia had not developed with occlusion up to twenty-nine minutes. Longer periods of time would probably be required to replace many aortic aneurysms with homografts.

The aorta may be occluded below the renal arteries for such long periods that time is not usually a factor when an aneurysm in this area is resected and a graft inserted. Cooley and DeBakey[3] were able to resect an aneurysm just above the diaphragm and insert a graft, there being forty-five minutes of occlusion with no neurological sequelae. However, it would obviously be desirable to utilize some method that would eliminate the risk of paraplegia during the insertion of a graft in the thoracic aorta.

Hypothermia may be used to extend the period of safe aortic occlusion by decreasing metabolic demands. The human aorta has been occluded at the level of the diaphragm for more than two hours under hypothermia with no ill effects.[4] This technique is relatively new, and is not without risk.

The two methods that were used by Carrel[5] more than forty years ago are of current interest. One was to by-pass the portion of the aorta being resected. Successful clinical use of this principle was recently reported.[6] The second method was to insert an intraluminal tube to maintain blood flow except for brief periods. We developed a modification of this method for use in the laboratory some time ago[7] and it has been used by a good many other investigators. We have recently used it successfully in two patients.

Read at the eighth annual meeting of the Society for Vascular Surgery, San Francisco, June 20, 1954.

METHOD

The aorta should be completely freed for a considerable distance on either side of the aneurysm. The aneurysm need not be completely freed for fear of rupturing into it. The length of the graft to be used should then be carefully measured. The proper sized glass tube should be selected. The tube may be of glass or heavy plastic, but it must have a good flange at each end. The reconstituted freeze-dried graft is placed over the tube in preparation for its use.

The two ends of the aorta may then be clamped and the aneurysm cut free from them. The aneurysm may be quickly evacuated to allow it to collapse, but time should not be taken to dissect out the aneurysmal wall. The glass tube is inserted in one end of the aorta and secured with a double turn of hernia tape as illustrated in Fig. 1, *A* and *B*. The other end is secured in like manner and the clamps are removed from the aorta. The blood flow to the lower extremities is then resumed.

The arterial graft previously placed on the tube is then sutured all the way around at one end and about two-thirds of the way around at the other end (Fig. 1, *C* and *D*). A tricky problem may be encountered in suturing the posterior wall of the anastomosis. After a little practice in the laboratory this becomes less difficult. If the tube is so large as to fit the aorta snugly, it may be very difficult. If the tube is only about two-thirds the size of the aorta, and the hernia tape around the aorta is placed well back from the end, no great difficulty will be encountered in the suturing. The entire graft should be rotated so that the initial suture is placed sufficiently posteriorly. A second suture may then approximate it as the graft is rotated in the other direction. These two continuous sutures may then be carried around to meet in front.

When all of one end and two-thirds of the other end are sutured, the clamps are applied, the tapes cut, and the glass tube slipped out of the remaining opening. The proximal clamp must be placed sufficiently high to allow for backing up of the glass tube until its distal end is even with the distal suture line. When the tube is out, the remaining suture line may be completed quickly and the clamps removed.

After the normal flow has been re-established, time may be taken to dissect free the aneurysmal sac and blood clot.

CLINICAL EXPERIENCE

Two patients have been successfully operated on by this method. The first was a man of 39 years who had a large syphilitic aneurysm distal to the left subclavian artery. His chest had been explored elsewhere one year previously. When seen by us, the aneurysm was so large that it almost completely occluded the trachea and the patient had great difficulty in breathing. At operation it did not seem feasible to clamp across the neck of the aneurysm and perform a lateral aortorrhaphy. We inserted a freeze-dried graft, using the shunting method described previously. The graft was 6 cm. long. When the aneurysm was dissected away from the spine, it was found that the verte-

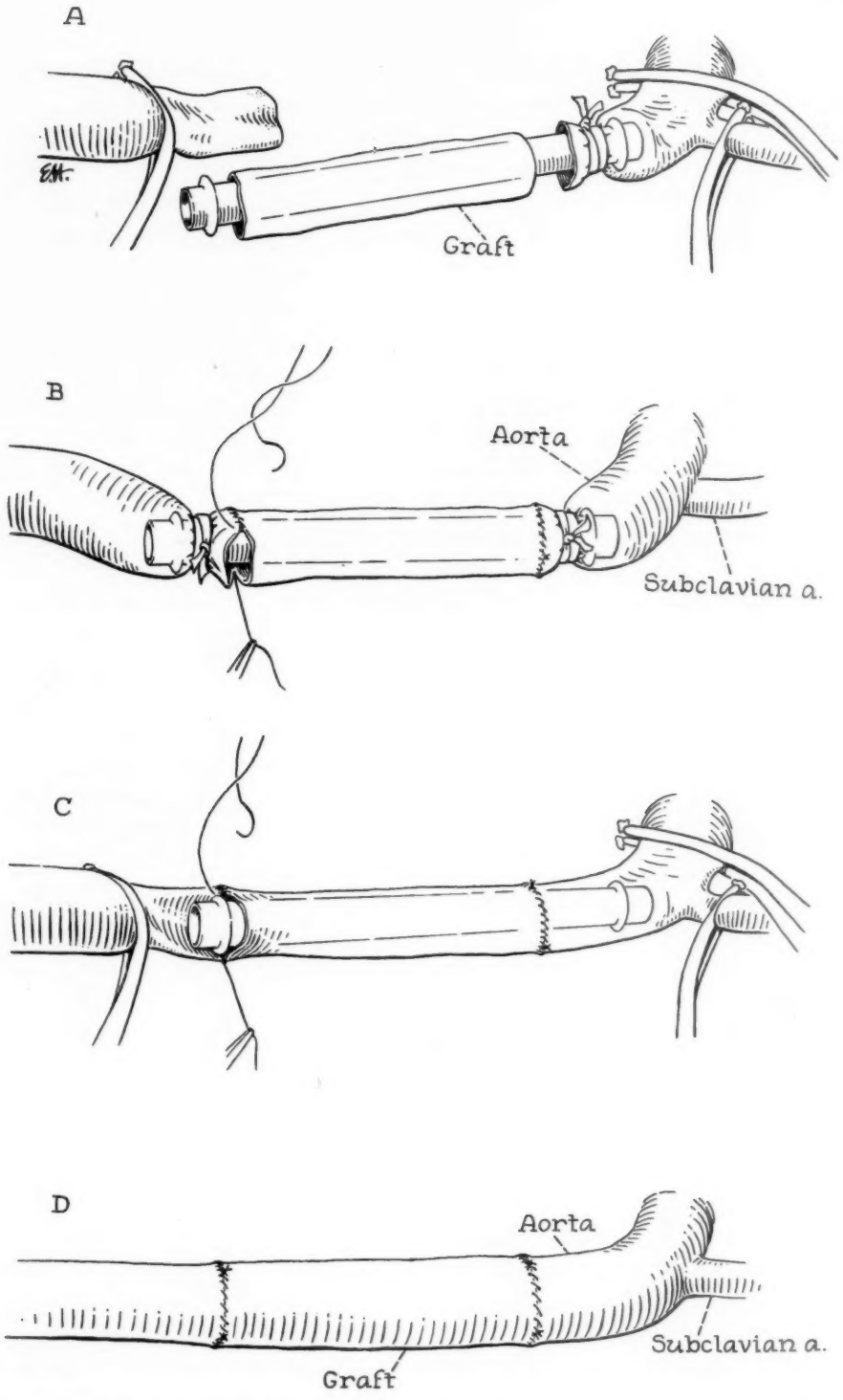

Fig. 1.—*A*, The graft is placed over the glass tube before it is inserted. The tube is anchored with a double turn of hernia tape.

B, All of one suture line and two-thirds of the other are completed while the blood is flowing through the tube.

C, The clamps are reapplied to the aorta, the hernia tape removed, and the tube slipped out through the remaining opening.

D, The suture is quickly completed before the clamps are removed.

bral bodies were badly eroded. We were fearful that this might injure the graft, but it has now been eight months since operation and the patient is back at work apparently without difficulty.

The second patient, aged 24, had an aneurysm just distal to the left subclavian artery. This aneurysm appeared to be a congenital one but there were no coarctation and no collateral circulation. In this instance, the aneurysm was so close to the subclavian artery that the hernia tape was tied proximal to it to allow an adequate cuff for suturing. The graft was 8 cm. long. It has been five months since operation and the patient is back at work.

In both instances the aorta was clamped for from six to eight minutes during the time the tube was inserted or taken out. The blood was flowing through the tubes for approximately one hour in both patients.

Hypothermia was also used in the second patient because of the fear that the left common carotid might require occlusion. This did not prove to be the case however.

SUMMARY

1. A simple method of maintaining blood flow through the descending thoracic aorta while inserting a homograft is reviewed.

2. Two patients have been successfully operated on by this method.

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THE USE OF THE ENLARGED LEFT SUBCLAVIAN ARTERY TO OVERCOME DEFECTS ASSOCIATED WITH COMPLICATED COARCTATION OF THE AORTA

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SURGICAL treatment has become accepted as the best method of relieving the hypertension associated with coarctation of the aorta. It also is the only means of preventing and treating the complications which develop from the malformation. Resection of the involved area, and establishment of a large lumen by direct suture of the divided ends, is fortunately usually possible, and is, of course, ideal. There are, however, a number of congenital and pathologic situations in which it is impossible to join the proximal and distal aorta without employing other means than direct suture. Among these are: atresia of the aorta involved in the coarctation, aneurysm, and marked arteriosclerotic changes.

To overcome these defects Gross used aortic homografts, thus finally applying in clinical surgery the suggestions and experimental work of the previous generation.[1-3] Such delays in acceptance or application of principles are numerous in surgery, another example being Souttar's[18] digital approach to the mitral valve. Gross's bold use of grafts in coarctation undoubtedly has served as a tremendous stimulus to the whole field of vessel grafting.

Despite the undenied great immediate mechanical advantage of using aortic homografts, there are still some doubts as to their long-term fate. It is recognized that such grafts serve as a scaffold into which the host grows a fibrous tube lined with intima. Under experimental conditions degenerative changes may be severe even in a few months, posing the question as to whether in time stenosis or aneurysm may occasionally result.[4] Difficulty in obtaining grafts and the uncertainty of their future have led to the use of various types of synthetic cloth tubes, but here, as well, we do not know their eventual fate.[5] One would like to use the patients' own transplanted vessels to avoid the possibility of difficulty years later, but experimental work on this point has not as yet come forward with any method which has gained general acceptance.

Such considerations are not so essential in the treatment of aneurysms of the abdominal aorta, where the lesion is merely an exaggeration of generalized arteriosclerosis. Furthermore, these aneurysms occur in an older age group with a comparatively shorter life expectancy than in treated coarctation of the aorta. In middle-aged patients with thrombotic occlusion of the abdominal aorta it might be a factor with which to reckon.

I have been able to find reports on thirty patients upon whom a subclavian-to-aorta procedure was attempted or completed.[9-15] Shumacker[7] has

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reviewed the literature on the subject. Apparently, the first successful end-to-end subclavian-to-aorta anastomosis was reported by Clagett[8] in 1947. Presumably, in most cases the defect was caused by a long segment of coarctation or atresia. In some instances exact details are not given as to whether the end-to-side or end-to-end anastomosis was performed. Again, the comparative sizes of the vessels and other local anatomic features are often lacking. However, one can deduce that fifteen patients had good to excellent results, and nine had only a fair or poor result; six died during or after operation. In any consideration of this subject one must remember that the procedure was used because of a very difficult or even desperate situation. No doubt in some instances grafts were not available.

We have been impressed with the size of the left subclavian artery associated with some coarctations in adults. Furthermore, it often curves off gradually toward its branches, without a sharp bend. It is this type of subclavian which seems most likely to succeed as a substitute for an aortic segment, and not those which have a sharp U-shaped bend, for in this type kinking and inadequate flow would certainly result. Shumacker[7] has suggested that the subclavian bend be reversed, as an autograft, to overcome this difficulty.

The purpose of this paper is to report the experience in two patients who have had end-to-end left subclavian-to-aorta anastomoses for the relief of complicated coarctation. In both instances conditions were favorable for using the subclavian and in both the results are very satisfactory.

CASE 1.—Q. D., aged 31. This patient had always been poorly developed, and as long as he could remember he had had difficulty keeping up physically with others. He gave a history of five or six episodes of chills and fever, which were thought to have been caused by subacute bacterial endocarditis. In recent years he had had fainting spells, suffered frequent headaches, and increasing dyspnea. Two years before entry at Stanford Hospital he underwent an operation for repair of the coarctation, but it was considered unfeasible because of the advanced state of arteriosclerosis near the coarctation.

During the two months before entry he had been largely confined at home, under digitalis treatment. On physical examination he was seen to be poorly developed. Marked pulsations were visible at the base of the neck. There were obvious large collateral vessels over the right shoulder, and a scar from the previous thoracotomy on the left. Blood pressures were right arm 202/102, left arm 204/108, left leg 100, right leg 104, by palpation of the weak dorsalis pedis pulses. Weak femoral pulses were present. The heart was enlarged to percussion. There was a harsh systolic murmur heard at the apex and along the left sternal border. Roentgenograms showed cardiac enlargement and rib notching. The electrocardiogram showed left ventricular hypertrophy.

At operation on March 17, 1953, a complete coarctation was found, with the distal aortic segment markedly arteriosclerotic and thrombosed. This was probably the site of the previous endocarditis. The proximal aorta was arteriosclerotic near the area of coarctation, obviously in poor condition for suturing. The left subclavian artery curved off gently to the left, and measured 23 mm. in diameter. It was estimated that resection of the diseased distal segment would cause a defect of 6 cm. The distal segment was fully prepared for anastomosis by ligating the area of coarctation and excising the involved tissue. The various branches of the subclavian were individually tied, and a Crafoord clamp was applied to the aorta proximal to the arteriosclerotic area. The subclavian was then cut, turned down, and anastomosed to the distal end with continuous everting and interrupted reinforcing sutures. No kinking occurred.

Recovery was uncomplicated. At this time, fifteen months after operation, the patient has lost most of his symptoms, has completed a course in a radio school, and is seeking employment. There are excellent femoral, popliteal, and pedal pulses, and the collateral vessels over the right shoulder have disappeared. No pulses can be felt in the left arm, but it has adequate circulation and is not disabled. Blood pressures in June, 1954, were right arm 140/70, right leg 140/80, left leg 140/90.

CASE 2.—R. G., aged 23. This patient was practically asymptomatic until he was 15 years old. He then began to have attacks of lightheadedness, nervousness, and occasional severe headaches. He frequently had a feeling of impending death. Leg cramps developed after strenuous exercise. Various treatments for hypertension had been employed before coarctation of the aorta was diagnosed. Upon examination there was a heaving pulse in the lower neck. Numerous collaterals were visible and palpable over the shoulders and back. The aortic, femoral, and popliteal pulses were absent. The blood pressures were: right arm 190/120, left arm 190/115, left leg -0, right leg -0. There was a loud systolic murmur heard to the left of the sternum. Roentgenograms showed an enlarged heart and rib notching.

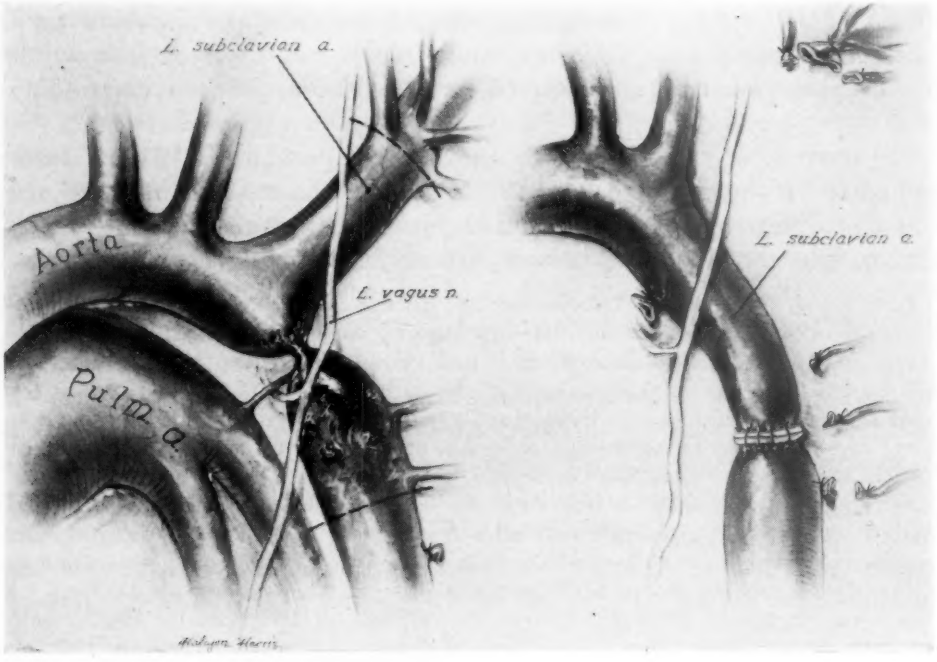

Fig. 1.—Case 1. Showing the arteriosclerotic involvement of the area of coarctation, with thrombosis of the distal segment. It is better to preserve the cross connections between the branches of the subclavian in order to preserve the collateral supply to the left arm.

On Nov. 6, 1953, thoracotomy showed a coarctation of the aorta with a 3 cm. aneurysm of the distal segment, arising at the first intercostal artery. It was estimated that resection of the aneurysm and the area of coarctation would cause a defect of 4 cm. The left subclavian artery curved off gently to the left, and measured 22 mm. in outside diameter. It was decided that this would serve well to replace the defect. The area of coarctation was oversewn with silk, and after several intercostal arteries were divided, the distal aorta was transected beyond the aneurysm. The branches of the left subclavian were preserved by placing a curved Potts clamp just proximal to them. This end was closed with continuous silk after the anastomosis was completed. A Crafoord clamp was applied to the aorta proximal to the coarctation, and the subclavian was cut just proximal to its

first branch. When reflected downward no kinking occurred, and a satisfactory anastomosis was accomplished by a continuous everting mattress suture posteriorly, and interrupted mattress sutures anteriorly.

Since operation he has had excellent femoral, popliteal, and pedal pulses, and the visible and palpable collaterals on his back and shoulders have disappeared. In June, 1954, the blood pressures were right arm 140/85, right leg 135/100, left leg 135/95. There were palpable left brachial and weak left radial pulses. He no longer has headaches or dizzy spells, his legs are warmer and stronger, and he has returned to work.

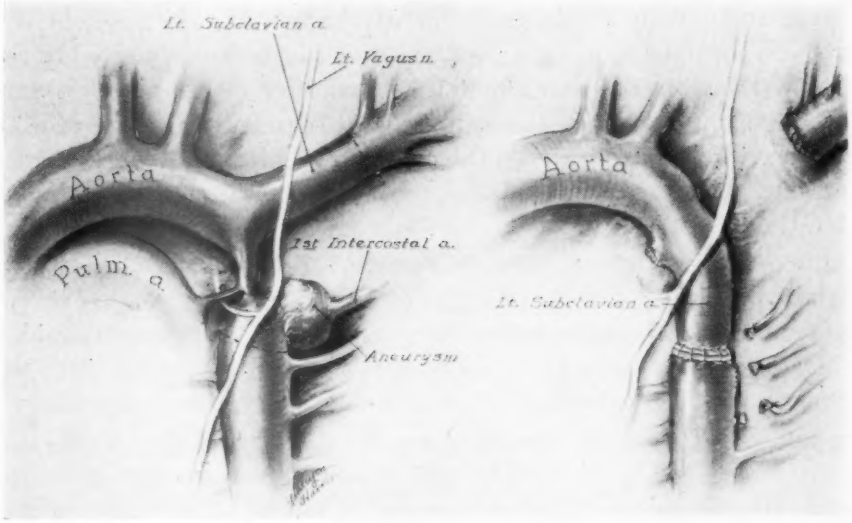

Fig. 2.—Case 2. Showing the aneurysm and other local anatomic features. In this instance cross-circulation to the left arm was preserved, and the patient has a radial pulse.

DISCUSSION

A number of objections have been raised as to the advisability of using the left subclavian artery to replace defects associated with coarctation of the aorta. The first is that in turning down the subclavian one eliminates a large number of collateral vessels which have been serving to by-pass the stenosis. This objection can be valid only if an adequate flow into the distal aorta is not accomplished by the anastomosis, for it is a common observation that the large anastomotic vessels seen in coarctation disappear after an adequate lumen is established. In fact, we have observed the collaterals to disappear after a successful operation upon a patient with coarctation associated with some narrowing of the aortic arch and a complete atresia of the left subclavian.[16] Presumably, more difficulties might arise from using the left subclavian in an end-to-side manner, as originally suggested by Blalock,[17] than end-to-end. It may also be held that the blood supply to the left arm might be impaired after turning down the subclavian, but in this situation the existing collaterals no doubt continue to serve a purpose, and the final condition would be better than in the many patients who have had the left subclavian used to create an artificial ductus.

To ensure the maximum benefit from cross-circulation through the branches of the subclavian, it is better to preserve the union of these vessels,

as was done in Case 2. Support of this technique is gained from the observation that this patient has palpable left brachial and radial pulses, whereas in Case 1, where the individual branches were tied, no radial pulse has returned, although the arm and hand have adequate circulation. In both of these patients all visual and palpable evidence of dilated collaterals in the shoulders and back have disappeared, indicating that the subclavian-aortic anastomosis has taken over their function.

Another consideration is possible cord damage from temporary occlusion of the large subclavian. This has evidently happened only once, in Blalock's case, but here thrombosis in an anomalous spinal artery was probably responsible. Should there be concern about the possibility of temporary ischemia of the cord, one should prepare the entire distal segment for anastomosis before clamping the subclavian, preserve the cross-circulation between the subclavian branches, and close the divided distal end after completing the shunt in order to shorten the time of occlusion.

This procedure is advocated only for the rare situation where a capacious left subclavian curves off without much of a bend at its origin. If there is any possibility of an inadequate flow after turning it down, one should use an aortic homograft, or possibly the reversed bend technique suggested by Shumacker.

Comparison of the final results from the use of end-to-end subclavian-to-aorta anastomoses should be made with results of treatment of complicated coarctation treated by graft. Furthermore, if fall in blood pressure is used as the measure of success, the comparison should be with patients in the same age group. It has been our observation, as well as that of others, that a complete restoration to a normal blood pressure often does not occur with even a large direct anastmosis in the older age group. The cause of this mild residual hypertension is not as yet explained, but it may be due to degenerative changes in the arterial bed which have come as a consequence of the prolonged hypertension associated with coarctation.

CONCLUSIONS

1. An enlarged left subclavian artery was used to bridge aortic defects in two instances of complicated coarctation of the aorta.

2. In the first case a 6 cm. defect resulted from the necessity of resecting a thrombosed arteriosclerotic distal segment. A left subclavian measuring 23 mm. in diameter was used to establish continuity, with an excellent result.

3. In the second case a 4 cm. defect resulted from a long coarctation and an aneurysm of an intercostal artery. A left subclavian measuring 22 mm. in diameter was used to establish continuity, also with an excellent result.

4. When the left subclavian artery is used in this situation, the continuity between its branches should be preserved in order to take full advantage of collateral circulation to the arm.

5. When anatomically feasible, this method of establishing continuity is considered to offer a better eventual prognosis than when a graft is used.

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SOME LONG-TERM OBSERVATIONS ON AORTIC HOMOGRAFTS

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DURING the past few years, there has been a great increase in the clinical use of preserved aortic homografts in the surgical treatment of aortic aneurysm, coarctation, localized malignancy, and even for superior vena caval obstruction. According to recent analyses by a number of surgeons,[1-13] the functional results have been very satisfactory with rare exceptions.[14-17] However, although significant dilatation or aneurysm of the graft has not yet been reported to our knowledge, there have been patients noted in whom calcification of the homograft has been demonstrated by radiography.[2, 13] Since many of the individuals into whom homografts have been implanted are young, it is of practical importance to learn as much as is possible regarding the long-term behavior of the aortic homograft.

Shorty after the initial reports by Gross and his colleagues, [18-20] we began an extensive study of the aortic homograft, designed to evaluate various methods of preservation and to analyze the condition of these grafts following implantation into well over 100 dogs for varying periods of time. This report presents our observations on eighteen aortic homografts which had functioned satisfactorily in the abdominal aorta for from eighteen months to four and one-half years. These grafts include those preserved at 4° C. in a balanced electrolyte solution* containing antibiotics and serum or serum ultrafiltrate, those preserved at either –27° C. or –70° C. after quick freezing, and those implanted in the fresh state (Tables I and II).

PREPARATION AND METHODS

The exact details of the preparation of the segments of aorta and of the actual techniques of preservation have been reported previously by us.[21, 22] The grafts used for implantation measured from 1.5 to 3.0 cm. in length and were implanted below the level of the renal arteries after excision of a comparable segment of abdominal aorta from the recipient dog. The anastomoses were made with a continuous everting mattress suture of 00000 Deknatel braided silk.† Heparin and Dicumarol were administered during the immediate postoperative period in certain of the dogs with quick-frozen grafts.[21] Penicillin was given daily for about one week following implantation in all animals. The subsequent functional status of the graft was estimated by palpation of the peripheral arterial pulses, and by aortography (Fig. 1, *A*).

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*Simms' X6 solution.

†Donated by J. A. Deknatel & Sons.

Since the present study concerns the behavior and condition of aortic homografts which had been functioning for long periods of time, we are reporting all those animals in which the homograft had been implanted for eighteen months or more.

TABLE I

DOG	AGE OF GRAFT (DAYS)	TIME IN DOG (YR.-MO.)	FUNCTION
	Fresh Aortic Homografts		
108	0	1-9	Satisfactory
436	0	4-0	Satisfactory
490	0	4-0	Satisfactory
	Preserved in Nutrient Electrolyte Solution at 4° C.		
38	120	1-6	Satisfactory
111	13	1-8	Satisfactory
318	1	2-0	Satisfactory
470	90	2-0	Satisfactory
314	1	3-8	Satisfactory
109	15	3-8	Satisfactory

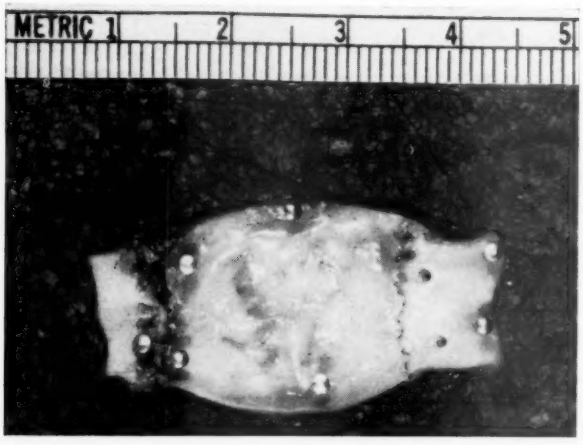
TABLE II

DOG	AGE OF GRAFT (DAYS)	TIME IN DOG (YR. - MO.)	FUNCTION
	Preserved in Air at –27° C.		
275	23	2- 2	Satisfactory
201	10	2- 6	Satisfactory
213	32	2- 6	Satisfactory
269	16	3- 0	Satisfactory
270	10	4- 6	Satisfactory
248	25	4- 6	Satisfactory
	Preserved in Air at –70° C.		
105	36	1-10	Satisfactory
677	25	2- 0	Satisfactory
77	73	3- 6	Satisfactory

At the time of sacrifice, the graft was exposed by laparotomy in the living animal, and generally under sterile conditions so that tissue culture studies of the graft and adjacent aorta could be conducted. The amount of adhesions and perivascular fibrotic reaction was noted, as well as the gross appearance of the homograft in the functioning state. Thus, any abnormal degree or constriction at the suture line or dilatation of the graft could be noted. Measurements were made to determine whether dimensional alterations had occurred. Once the graft was excised with at least 1 cm. of adjacent aorta, it was opened in its long axis for close inspection of the luminal surface. Areas of degeneration were noted, as well as the degree of thinning of the wall of the homograft. A 2 mm. strip was removed for tissue culture studies, the technique of which has already been described.[21, 23] Following this, the graft was photographed and fixed. After twenty-four hours in Bouin's fixative, the graft was transferred to 80 per cent ethyl alcohol and processed in the laboratory of surgical pathology. All sections were stained by hematoxylin and eosin, trichrome stain, and Verhoeff's elastic tissue stain. In a few instances

tension studies were performed on the graft and on the adjacent aorta. In some dogs, the uptake by the graft and normal aorta of T 1824 or radioactive sodium was studied.

A.



B.

Fig. 1.—*A*, Aortogram showing fresh aortic homograft four years following implantation. The satisfactory function was confirmed at autopsy (Dog 490).

***B*, Specimen of graft shown by aortography. There is slight dilatation, calcification, and moderate thinning of the graft.**

RESULTS

Condition of the Homograft at the Time of Implantation.—

Fresh grafts: In three dogs, segments of aorta were implanted which were obtained at the time of operation from other dogs. Hence, these grafts were in the completely fresh state, and without any preparation or storage before use. One graft was excised after one year and nine months; the remaining two were removed after four years of function (Table I).

Nutrient grafts: In six dogs, segments of aorta were implanted which had been maintained at 4° C. in Simms' X6 solution, containing either 10 per cent homologous serum or 33⅓ per cent bovine serum ultrafiltrate, and antibiotic drugs. The period of storage ranged from one day to four months (Table I).

At the time of use, these grafts were pale but had excellent elasticity and normal thickness of the wall. They did not appear to be friable and sutured well. All but one of these (Dog 38) were studied by tissue culture at the time of implantation. With the exception of the 3-month-old graft (Dog 470), the other nutrient grafts, which had been stored for from one to fifteen days, all were viable. The microscopic picture revealed a loss in endothelial, smooth muscle and fibroblastic cells, proportional to the duration of storage. The fibroblast was most resistant to destruction, persisting in some instances for two months. The endothelium generally degenerated within a few days to weeks. The elastic fibers became thickened, and segmentation and splitting were noted after a few weeks of storage. These grafts were implanted for from one and one-half years to three years and eight months (Table I).

Quick-frozen grafts: In nine dogs, segments of aorta were implanted which had been frozen rapidly at the time they were obtained. In most instances, a mixture of carbon dioxide ice and 95 per cent ethyl alcohol was used to lower the temperature, but one graft (Dog 77) was immersed in liquid air. The frozen segments were then stored at subzero temperature, six at –27° C. and three at –70° C., for from ten to seventy-three days before implantation (Table II).

At the time of use, these grafts were very pale and demonstrated a diminished elasticity and turgor. In those stored at –27° C., there appeared to be a progressive diminution in thickness of the wall during storage. In four dogs in which these grafts were implanted, anticoagulant drugs were administered. None of the grafts which had been stored in air at these subzero temperatures exhibited cellular growth by tissue culture[21] at the time of implantation. Microscopic examination of the frozen homografts revealed loss of endothelial, smooth muscle and fibroblastic cells of a greater degree than that observed in the nutrient grafts stored for comparable periods of time. Among the grafts stored at subzero temperatures, the rate and degree of degeneration of the graft were greater in those stored at –27° C. than in those kept at –70° C. These grafts were implanted for periods of from one year and ten months to four and one-half years (Table II).

Condition of the Homograft at the Time of Excision.—

Gross appearance: The entire group of homografts will be described since there were no distinguishing characteristics which would serve to identify them on the basis of the method of preparation. As was noted in our previous publications,[21, 22] there is a heavy investment of the graft by fibroblasts from the recipient following implantation of a homograft. This inflammatory reaction reaches a peak at about the third week, if gauged by fibroblastic growth in tissue culture,[21] and subsides by the twelfth week. Thereafter, there is no gross recognizable diminution of the fibroblastic layers nor of the thickness of the graft wall until about eighteen months. Then a progressive reduction is observed, so that by three or four years, there is generally very slight fibrous reaction about the graft, and moderate to marked thinning of the homograft is observed (Fig. 1, *B*). Indeed, significant thinning of the graft was observed in fifteen of the eighteen animals killed from eighteen months to four and one-half years after implantation. The three in which no significant thinning was noted were nutrient grafts functioning for two years or less (Table III).

Table III. Gross Pathologic Changes

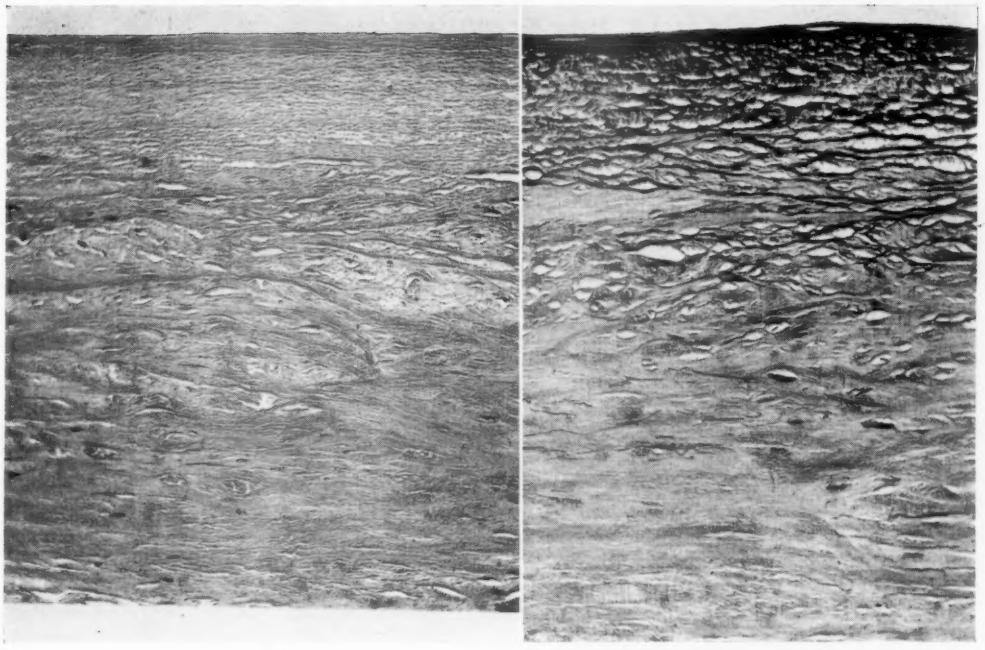
DOGS		THINNING	DILATATION	EROSION	CALCIFICATION
Frozen					
−27° C.	6	6	1	0	3
−70° C.	3	3	2	1	0
Nutrient at					
4° C.	6	3	3	0	4
Fresh	3	3	1	1	1
Total	18	15	7	2	8

Dilatation of the graft was observed occasionally in all types of the homografts, being noted even in one fresh homograft (Table III). However, it was minimal in all specimens and generally approximated that noted at the time of implantation. Aneurysm was not encountered.

A circular intimal defect, usually 2 to 4 mm. in diameter and located in the mid-portion of the graft, was noted in two instances (Table III). Gross calcification occurred in eight of the homografts. This was either in small localized deposits or diffusely distributed throughout the grafts, and was noted in all types of homografts (Table III).

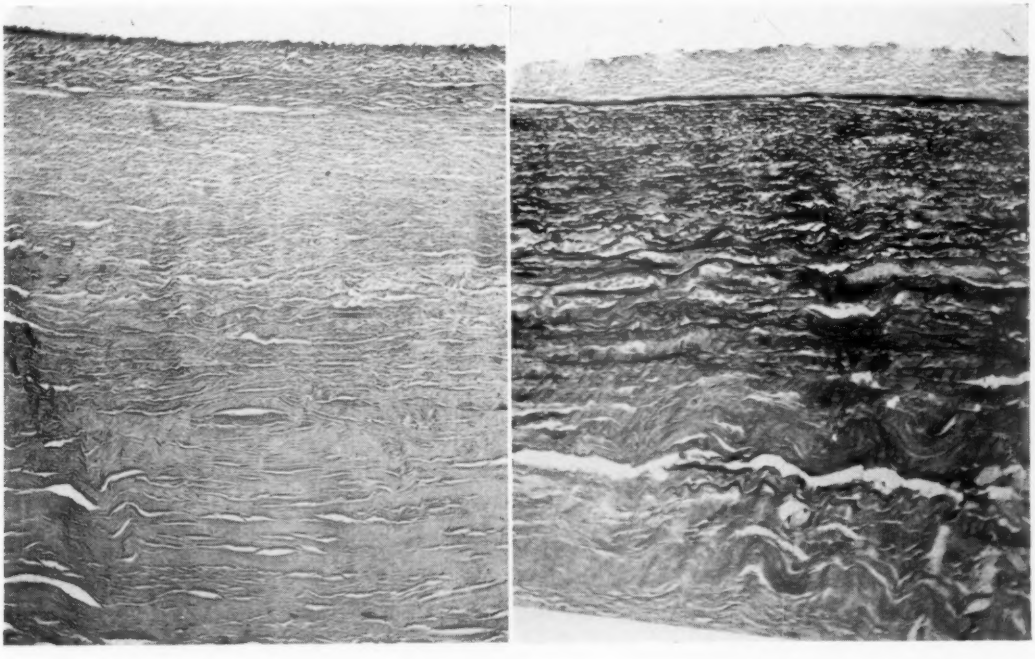
Microscopic pathology: Regardless of the method of preservation, similar histologic changes were found in all the aortic homografts. These same changes were observed in the fresh homografts as well (Figs. 2, 3, and 4).

The intimal lining of the graft, presumably derived from the fibroblasts and possibly endothelium of the adjacent host aorta, covers the inner surface of the homograft within a few weeks of implantation. The highly cellular, multilayered intimal zone is markedly thicker at each end of the graft than in the mid-zone, and remains a discrete layer separate from the homograft. After some months, a progressive change is observed with thinning of this layer and organization into well-differentiated collagen fibers. Scanty fibroblasts may be



A. *B.*

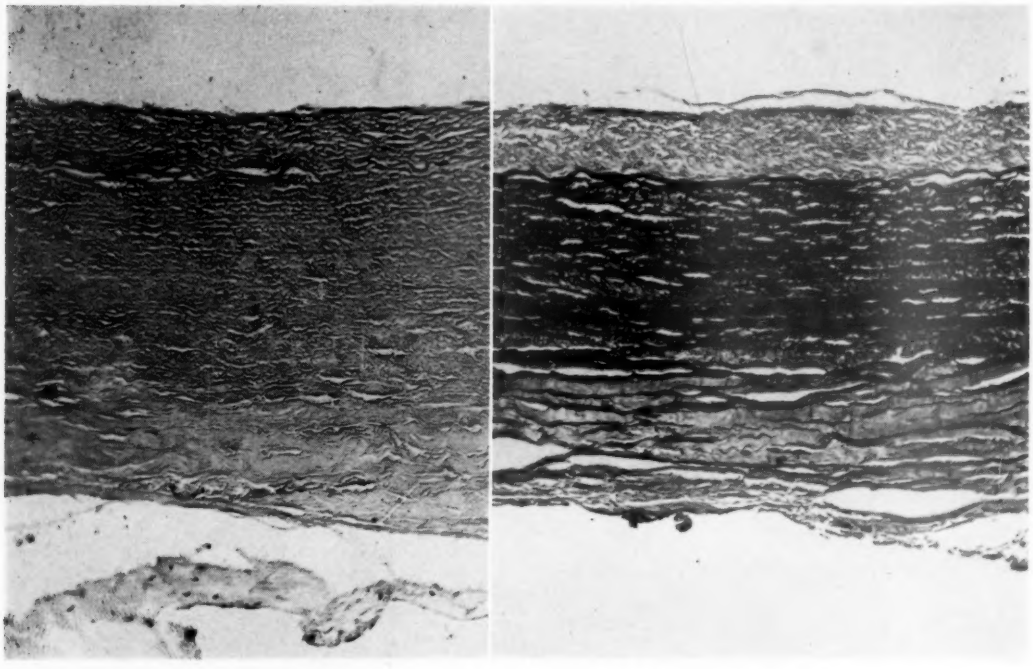
Fig. 2.—Photomicrographs of fresh aortic homograft in dog for four years (Dog 436). In the mid-portion of the graft, the intima is very thin and contains few cells. The narrow hyaline, acellular band beneath the intima represents the original homograft. The very wide outer zone is composed of fibrous tissue and fibroblasts derived from the host animal. *A*, Hematoxylin and eosin stains (×150, reduced ¼). *B*, Verhoeff's elastic stain (×170, reduced ¼).



A. *B.*

Fig. 3.—Photomicrographs of aortic homograft in animal for three years and eight months (Dog 109). The graft had been preserved at 4° C. in Simms' X6 solution containing 10 per cent homologous serum for fifteen days before use. The increased thickness of the intimal zone near the end of the graft is noted. This layer contains fibroblasts, but no elastic fibers. The original homograft is acellular and contains an elastic framework in which a patchy loss of fibers is observed. The individual elastic fibers are deeply staining and are fragmented in areas. The fibrous zone derived from the host is seen external to this layer. *A*, Hematoxylin and eosin stains (×170, reduced ¼). *B*, Verhoeff's elastic stain (×150, reduced ¼).

seen after a few years, scattered through the matrix. No new elastic fibers have been observed although endothelial-like cells have been identified histologically and by tissue culture.[21-23] In those specimens with an intimal defect observed grossly, this layer was absent at these sites. After two years, the layer could be stripped easily from the graft in many instances.



A. *B.*

Fig. 4.—Photomicrographs of aortic homograft in dog for four and one-half years (Dog 248). The graft had been frozen rapidly in carbon dioxide ice and ethyl alcohol and then stored at −27° C. for twenty-five days before use. This section represents the same portion of the graft shown in Fig. 3. Note by comparison the progressive thinning of the graft and outer zone which has occurred. In this graft, the elastic fibers have stained more heavily, but show the same type of degenerative changes as observed in that of Dog 109. *A*, Hematoxylin and eosin stains (×170, reduced ¼). *B*, Verhoeff's elastic stain (×170, reduced ¼).

The medial zone of the excised transplant appears as a homogeneous, acellular, narrow band when stained with hematoxylin and eosin. This zone becomes thinner with time, and appears to represent the entire original homograft. There is little or no infiltration of this layer by fibroblasts or other elements of the host, unless infection occurs. At such a time, polymorphonuclear leukocytes may permeate the layer. This was not observed in any of the long-term specimens. Calcification was noted in this zone or in the intima in eleven of the eighteen homografts (Table IV), being present in three which appeared free of calcium by gross inspection. This deposition occurred most often in the portion of the transplant adjacent to the suture lines, and may be related to the compression of the tissue at this site. Calcification occurred equally in the nutrient and quick-frozen homografts, and was observed in the fresh homografts as well (Table IV). The elastic framework of the original graft occupies the medial zone of the transplant, and undergoes alterations soon after implantation

of the homograft. As the cellular elements of the graft disappear, the elastic framework becomes narrowed. The individual fibers become condensed, fragment, and have an altered staining reaction. These degenerative changes continue during the period of implantation, and after two years there may be scattered areas in which the elastic fibers actually disappear. The internal elastic membrane was present in most specimens, but it was fragmented in places. These changes were noted in all types of homograft (Fig. 5).

TABLE IV. MICROSCOPIC PATHOLOGIC CHANGES

DOGS		MURAL THROMBUS	CALCIFICATION	ELASTIC DAMAGE
Frozen				
−27° C.	6	1	4	6
−70° C.	3	1	1	3
Nutrient at				
4° C.	6	2	4	6
Fresh	3	2	2	3
Total	18	6	11	18

In a few grafts, there was a discrete disruption through the entire thickness of the elastic framework. Into this area had grown intimal tissue, and in one (Dog 77), the tissue filled the defect across the entire thickness of the original graft and into the adventitial zone (Fig. 6). This graft had been cooled rapidly in liquid air, and may have cracked in the process. Such localized and discrete disruptions might well be related to factors at play in the period prior to implantation. If we assume that this disruption occurred prior to implantation, there would be real significance in the fact that no localized thinning or aneurysm formation developed during three and one-half years of function.

The outer fibrous zone of the excised transplant is derived entirely from the adjacent tissues of the recipient animal. The connective-tissue investment, so dense during the first eighteen months, progressively becomes less cellular and becomes organized collagen. The entire layer thins with time, and after three years, this reduction in the fibrous reaction is reflected by the ease with which the graft is mobilized from its bed at the time of excision.

Tissue culture studies: The technique employed has been described previously,[21-23] and the details of the study of these homografts will be presented separately. Nevertheless, there were several important observations which deserve mention in this report. At the time of implantation, about 25 per cent of the homografts had viable fibroblasts demonstrated by culture. These were the nutrient grafts stored for less than three months (Table I). However, at time of excision the growth pattern was essentially the same for all the homografts with a progressive reduction in cellular growth noted in proportion to the time of implantation. The growth was predominantly fibroblastic, and there were noted degenerating cells, debris, macrophages and lipoid droplets (Fig. 7). In some cultures, sheets of cells believed to be endothelium were observed.

None of these grafts had a growth value equal to 50 per cent of the growth obtained from the same tissue at the time it was obtained originally. Growth

was especially poor after two years of implantation. Growth of cells from the aorta adjacent to the graft was less luxuriant than that of control aorta, which suggests that some extrinsic factor might play a part. When T 1824 was injected intravenously twenty-four hours before sacrifice of dogs with grafts im-

A.

B.

Fig. 5.—*A*, The elastic fibers of normal fresh aorta stain less deeply than those of an aortic homograft. They are widely separated by smooth muscle cells and fibroblasts of the media. Verhoeff's stain. *B*, The elastic fibers of an aortic homograft three years and eight months after implantation are deeply staining, condensed, and often fragmented (Dog 314). Verhoeff's stain (×1,140, reduced ⅓).

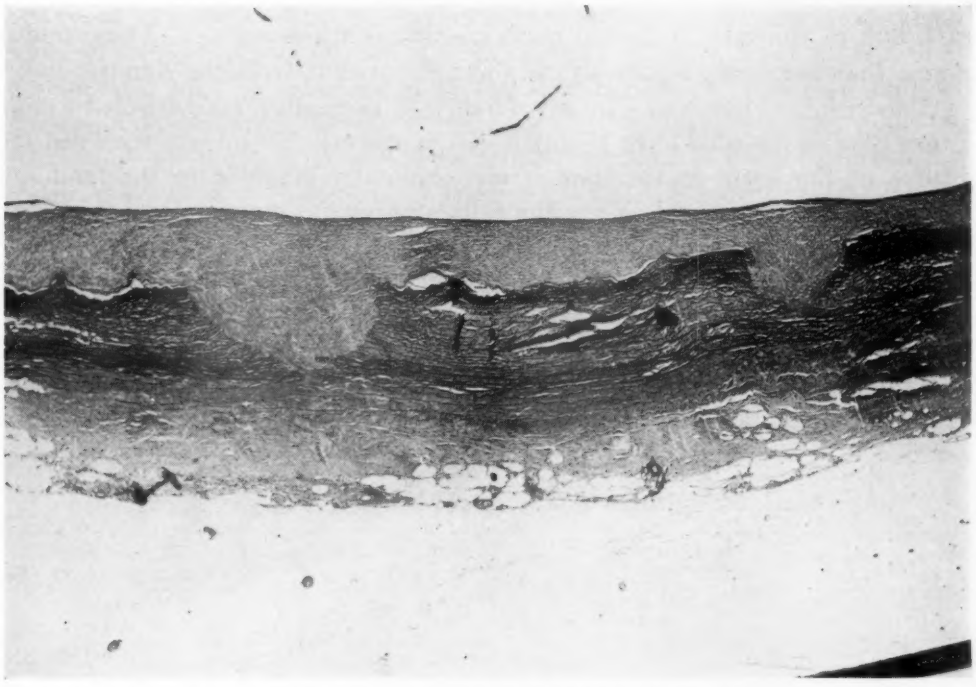


Fig. 6.—Photomicrograph of aortic homograft which had been frozen rapidly in liquid air and then stored for seventy-three days at −70° C. before use. It had functioned well for three and one-half years, but microscopic examination revealed areas in which the elastic framework had been completely disrupted (Dog 77). Verhoeff's stain (×50, reduced ¼).

Fig. 7.—Photomicrograph of living culture of a quick-frozen homograft, removed over two years following implantation (Dog 275). The predominant growth is fibroblastic. Also present are degenerating cells, macrophages, and debris (×420 unstained, reduced ⅓).

planted only a few weeks, it was noted that the aorta between the site of application of Potts clamps and the graft stained a deep blue, as did the homograft, and in contrast to normal aorta elsewhere in the animal. These findings suggest that persistent injury to the aorta may result from the clamp.

The average growth of a group of fourteen excised grafts subjected to tissue culture studies revealed only 18.2 per cent of the cellular growth recorded from cultures of the aorta at the time it was originally obtained in the fresh state from the donor dog (Table V). The cellular growth obtained from the graft is believed to be from cells derived from the host, rather than from cells of the original graft. The aorta adjacent to the graft grew only 36.4 per cent as well as control normal fresh aorta. In turn, the graft at time of excision grew only 50 per cent as well as the aorta adjacent to the graft. This poor growth value of long-term grafts is completely in agreement with the histologic evidence of progressive reduction in cellularity of the graft and of the investing fibrous tissue.

TABLE V. RATIOS OF FIBROBLASTIC GROWTH BY TISSUE CULTURE

TYPE OF GRAFT	EXCISED GRAFT: FRESH AORTA (%)	ADJACENT AORTA: FRESH AORTA (%)	EXCISED GRAFT: ADJACENT AORTA (%)
Nutrient	21.0	46.5	44.5
Frozen −27°	17.5	32.5	53.8
Frozen −70°	11.4	25.7	44.5
Average	18.2	36.4	50.0

Uptake studies: When a solution of T 1824 (Evans blue) was injected intravenously into a dog twenty-four hours before sacrifice, the normal aorta stained a pale aquamarine blue. There was no difference in the staining capacity of these hemografts, excised after more than eighteen months of implantation, which suggests that the luminal surface had developed a nonwetting layer of cells similar to, if not actually, endothelium.

The uptake of radioactive sodium was studied in only one animal (Dog 270). The homograft had been quick-frozen before implantation and was excised after four and one-half years of function. Five hours after the intravenous injection of 125 millicuries, the dog was killed and counts made of an 8 by 4 mm. strip of homograft and of normal aorta. The values were 19 and 43 counts per minute, respectively, revealing a less amount from the homograft.

Tension studies: An apparatus* for recording the pattern of "give" to a progressive increase in tension on the graft to a total pull of 85 grams was used in a few instances. The normal aorta responded to tension with a gradual curve being produced (Fig. 8). This type of curve is believed to represent the resistance offered by viable smooth muscle, fresh elastic tissue, and living fibrous tissue. On the other hand, a long-term homograft produced a low, flat response with little curve. This is the pattern produced by fibrous tissue and degenerated elastic fibers. The increase in length of normal fresh aortic strips averaged about 25 per cent, whereas that of the homograft ranged from 5.5 to 14.3 per cent, thus reflecting far less elasticity.

*Lent by the Naval Medical Research Institute, Bethesda, Maryland.

DISCUSSION

The experimental studies of aortic homografts which have appeared in the literature have generally been of little more than one year in duration at the time of reporting. In our previous publication of results of studies of comparable duration,[21, 22] we predicted that the degenerative changes observed at that time in homografts would be more prevalent in older specimens and that these alterations were characteristic of aortic homografts per se, and not related to the method of preservation. The results reported in this paper

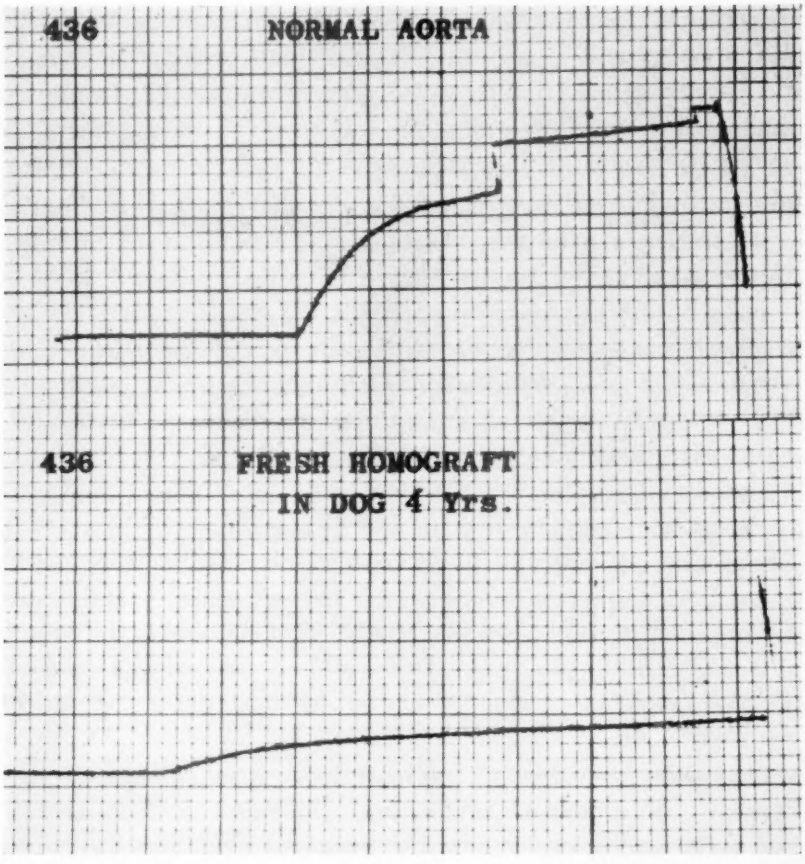


Fig. 8.—Tension curves of fresh control aorta and of excised homograft which had functioned for four years (Dog 436).

strongly verify those anticipations. The calcification observed in the forty-three homografts in the abdominal aorta reported in 1951 amounted to 11 per cent, whereas that observed in these eighteen long-term homografts amounts to 60 per cent. Further significance is lent to these figures by the recent findings of Harkins and co-workers that in growing pigs there is a much higher incidence of degeneration in homografts implanted into the thoracic aorta as compared to those in the abdominal aorta.[24] The degree of calcification observed in a relatively short-term follow-up in the abdominal aorta amounted to 15 per cent, which agrees closely with our observations. This suggests that

long-term follow-up of homografts implanted into the thoracic aorta might well reveal even more serious degrees of degeneration than those reported in our animals.

The consistent alterations observed by us in the elastic fibers in the long-term aortic homograft have serious implications if one considers the elastic framework of a major artery to be the most important factor determining the strength of the tissue. If one adds to the disruption of the elastic framework a marked thinning of the wall and loss of cellular elements, there might appear to be an adequate basis for the later development of an aneurysm. Grindlay[25] reported the occurrence of an aneurysm in an aortic homograft implanted for two years in a dog. Nabatoff and associates[26] have observed consistent aneurysm formation in autologous vena caval transplants into abdominal aortas of dogs after two years. Johnson and co-workers[27] have also noted aneurysm in venous transplants.

In the fear that these late pathologic changes in aortic homografts might predispose to aneurysms in some instances, a technique of adding external elastic support to such grafts by means of nylon tulle-woven netting was developed in our laboratory.[28] Experimentally, it prevented elongation and significant dilatation in a series of autologous grafts of external jugular vein and pericardium implanted in dogs. Consequently, this material has been employed about grafts in twelve human cases, and has been well tolerated in all. Only time will determine the value of this method.

Our laboratory experience with the freeze-dried aortic homograft is not sufficiently long for comparison with the grafts reported here.[29] There appears to be less fibrous reaction about them after implantation, and they seem to thin sooner than the other homografts. The same degenerative changes are noted after implantation as are characteristic for homografts, including calcification and elastic fiber changes. However, because of the ease of storage, the freeze-dried graft has become perhaps the most popular type for clinical use at the present time.

There has been considerable interest in light-weight cloth woven with plastic filament. Voorhees, Jaretzki, and Blakemore[30] and later D'Angelo, Benson, and Grimson[31] have reported experimental success in bridging aortic defects in dogs by means of tubes fashioned from Vinyon-N cloth. Subsequently, Blakemore has enjoyed success in human cases with aneurysms of the abdominal aorta. Hufnagel and Rabil[32] and others have employed Orlon cloth in dogs with good function resulting. Additional reports by Hufnagel[33] and by Shumacker and associates[34] attest to functional success with plastic prostheses in the aorta. We have had experience with cloth prostheses of Vinyon-N, Orlon, Dacron, and nylon and agree that if properly handled, they do demonstrate encouraging functional success, becoming infiltrated and lined by fibrous tissue. Wesolowski and his co-workers[35] as well as Shumacker and co-workers[34] have noted calcific deposits beneath the intima of Orlon or nylon prostheses as well as a tendency to thrombosis in smaller

arteries. Thrombosis will occur particularly if there is a wrinkle or ridge in the plastic prosthesis. If, after a long time in the body, there is no depolymerization or other significant chemical change to cause destruction of the plastic filament, plastic prostheses should serve a useful role in vascular surgery. We have been disappointed with tubular grafts of Ivalon sponge, and will report our findings elsewhere.[36] Grindlay and Kirklin[37] have had better results with this material. The ability of some of these plastics to produce sarcoma in a susceptible strain of rat has been observed by Oppenheimer and associates.[38] Their studies are continuing, and although it is difficult to draw clinical conclusions from this work, it does merit attention.

In conclusion, it is evident that experimental work is still needed and is being carried out in the field of blood vessel replacement. Although there is real promise in plastic cloth prostheses, most surgeons continue to rely on the use of aortic homografts at the present time. It is important for them to know the progressive alterations which develop in these implants, and be watchful for alterations in function and form of grafts which have by necessity been employed in patients. It would be unfair to consider calcific deposition and thinning of homografts alone to be contraindications to their use. Nevertheless, one cannot deny that thinning and degeneration of the elastic layers may well set the stage for the development of aneurysms. We have used nineteen aortic homografts in patients at the Presbyterian Hospital since early in 1950, and except for calcification which has developed in the first graft used (coarctation), we have observed no significant abnormalities in these grafts. Three patients died of causes unrelated to the grafts, and at autopsy, the homograft appeared very satisfactory. We will continue to use them when really necessary, but feel obliged to urge vascular surgeons to employ vessel replacements only when absolutely vital to the success of the operation.

SUMMARY

Eighteen aortic homografts implanted into the abdominal aorta of dogs have been studied from eighteen months to four and one-half years after implantation. Function was excellent in all, and no aneurysms were noted. However, calcification and marked thinning were observed grossly. Microscopic examination revealed condensation of the graft with complete loss of cellular elements, and a thinning of the internal and external layers which developed from the fibroblasts of the recipient animal. Most significant was the marked degeneration of the elastic fibers of the homograft. The consistency of these changes, despite method of preservation of the graft, indicated that they are characteristic of aortic homografts per se. The marked degree of such alteration in some of these long-term grafts raised a question as to whether aneurysm might not ultimately have formed.

We wish to acknowledge the valuable help of Dr. Shivaji Bhonslay in performing the uptake and tension studies, and the interest and advice of Dr. Raffaele Lattes in the interpretation of the microscopic preparations.

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PLIABLE PLASTIC TUBES AS AORTIC SUBSTITUTES

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ALTHOUGH autogenous veins have served well for replacement of segments of peripheral arteries in man, their use as aortic substitutes is contraindicated. For one thing autogenous veins which can justifiably be sacrificed as a source for the graft and which are of suitable size and length are not available. For another, in contrast to the good results obtained from the use of vein transplants in the extremities, long-term experimental studies reveal a significant incidence of aneurysmal dilatation of vena caval transplants to aortas. Homologous aortic grafts have been used with success in patients. They have continued to function well over a period of years, and roentgenographic evidence of calcification has been rather low.[1] It has, of course, long been known that both fresh and "preserved" arterial homografts fail to survive as living structures, degenerate entirely, or in large part, and are replaced by host tissues. At least one clinical homologous aortic graft gave rise to an aneurysm which brought about the death of the patient six months after implantation.[2] Nevertheless, the results with their use to date have been eminently successful. It is not known whether difficulties will ultimately be encountered from any degenerative changes which may occur. A persistent and trying problem concerns their acquisition. In spite of the recent progress made in the preservation, sterilization, and storage of homografts, most institutions find it difficult to obtain material adequate for their needs. It would obviously be advantageous if one could utilize tubes made of readily available plastic material.

Most efforts at permanent intubation of arteries with rigid tubes of inert materials have not proved successful because of the high incidence of thrombosis and the great hazard of necrosis and hemorrhage when they are secured to the ends of aorta by encircling ligatures. The use of such tubes made of glass, plastics, and various metals has generally resulted in failure. Hufnagel and Gillespie[3] did, however, demonstrate that highly polished tubes of methyl methacrylate remained patent when interpolated in the aortas of dogs. They found that the danger of ischemic necrosis of the aortic wall which so often occurs beneath the holding ligature could be avoided by a technique of "multiple point fixation." Indeed, by following this principle, Hufnagel and his associates[4] have been successful in inserting short valve-containing tubes of

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plastic material in patients with aortic insufficiency. Ideally, if a plastic aortic substitute were developed, it should be one which is readily available, inexpensive, easily made into tubes of various sizes and shapes, sterilizable, pliable rather than rigid, easily affixed to the ends of the blood vessel by ordinary vascular suture techniques, nonreactive, and of such a character that it would become incorporated into a newly formed vessel laid down by the host.

A significant contribution in this direction was published in 1952 by Voorhees, Jaretzki, and Blakemore.[5] They demonstrated that short tubes made of Vinyon-N could be sutured to the divided ends of aortas of dogs with continued patency. A new smoothly lined fibrous aorta developed about the plastic material with the passage of time. Recently a few of these animals have been sacrificed two years after insertion of a graft. These grafts have been found to be in good condition.[6] Interest in the possible use of plastic materials for this purpose arose in our laboratory as a consequence of observations made upon finely woven nylon cloth placed within the heart for closure of atrial and ventricular septal defects.[7, 8] It was noted that this material was well tolerated and became covered with a glistening endothelial-like membrane. It is the purpose of this report to describe our initial experiences.

MATERIALS AND METHODS

Healthy mongrel dogs ranging in weight from 11 to 19 kilograms were used. They were anesthetized with intravenously administered thiopental, and anesthesia was continued with an ether-oxygen mixture delivered through an endotracheal tube by means of an intermittent positive pressure apparatus. All operations were performed with an aseptic technique. The abdominal aortas were exposed through a long midline incision. The thoracic aorta was exposed through a long left lateral seventh intercostal incision. An appropriate number of lumbar or intercostal arteries were divided between ligatures. The size of the aorta to be resected was measured as accurately as possible by temporarily cross-clamping it with a Potts ductus clamp and measuring the flattened-out half circumference. The length of the segment to be excised was also measured carefully. A graft of suitable size and length was selected. The aorta was occluded above and below with Potts ductus clamps, a segment was excised, and the graft was sutured in place with 00000 arterial silk, using swedged-on small round needles. Some of the grafts were fixed to the aorta with a continuous over-and-over suture, carried out in such a way as to approximate the inner surfaces. In the remainder, everting mattress sutures were used. In a few, interrupted everting mattress sutures were employed. In a few, simple continuous everting sutures were used. In most of this group a continuous everting mattress suture was placed in such a way that after placement of each mattress the suture was passed through the everted edges as a simple over-and-over locked stitch.

After insertion all grafts were covered with pleura or peritoneum. To prevent ischemic paralysis from prolonged occlusion of the thoracic aorta, a few pilot cases were operated upon using a polythene tubal shunt, as large as

possible, between the left carotid artery and the right femoral artery. This method was found to be much less satisfactory than a technique using hypothermia, which was employed in all but a few instances. The animal was placed on his side on a plastic bag containing crushed ice, and the rectal temperature was checked. The temperature was lowered to from 30 to 32° C. and not allowed to fall below 28° C. The aorta could safely be occluded for one-half to one hour while the anastomoses were being accomplished. No special attention was given to the process of rewarming above 30° C., but below this level the animal was continued on oxygen via the endotracheal tube, until the temperature reached 30° C.

The preparation of the grafts was standardized. The basic material was finely woven nylon having 277 by 240 strands per square inch.* It was fashioned into tubes with diameters of from 0.6 to 1.0 cm. The tubes were made by sewing the sides of the folded cloth with a sewing machine using fine nylon thread placed twenty-five stitches per inch. Initially nylon alone was used as the plastic graft. These studies are not included in this report since use of this material was frought with alarming bleeding directly through the wall of the tube. To lend impermeability to the graft, a thin film of polythene† was fused between two sheets of nylon by pressing with an adjustable flat iron turned to "wool." After this material was prepared it was made into tubes as described previously. A second type of graft was made of a single sheet of nylon which had been dipped into methyl methacrylate dissolved in a commercial solvent of unknown formula, allowed to dry, and redipped. This material was then sewn into a tube in the standard manner, following which the suture line alone was recoated with methyl methacrylate by swabbing.

OBSERVATIONS ON GRAFTS MADE WITH NYLON AND POLYTHENE

Tubes made of a double layer of nylon and a single layer of polythene were used as grafts in twenty-seven dogs (Table I). Twelve grafts were placed in the abdominal aorta and fifteen in the thoracic aorta. Seventeen of these grafts were 1 cm. in diameter. They ranged in length from 5 to 10.8 cm. Three were 10 cm. in length or greater and 10 were 7.5 cm. in length or more. Their average length was 7.5 cm. The interval of time between insertion of the graft and post-mortem study ranged from two to 310 days. Eight were two months or more old; six, four months or more in age; five, six and one-half months or more in age; and the oldest was approximately ten months old. All the grafts remained patent except one (637). In this exceptional case the graft was noted at the time of operation to be too long for the aortic defect with resultant obvious buckling. In two animals (858, 856) the operator felt that the continuous everting mattress sutures with simple locked sutures of the everted edges were placed too closely together and too tightly, and in both instances late disruption of the distal anastomotic line, on the tenth and twentieth days, respectively, occurred with fatal hemorrhage. With the ex-

*Obtained from Stehli Company, Inc., 1372 Broadway, New York, 241F nylon fabric.

†Obtained from the Clay-Adams Company, Inc., 308 W. Washington Street, Chicago, PE 2600 Polyethylene film, 0.0015 thickness.

ception of these three cases, the operator felt that the interpolation of the graft was accomplished in a satisfactory manner and in none of them was any difficulty encountered. Of these fourteen animals with technically satisfactory placement of the graft and good ultimate result, three were carried out with everting mattress sutures and the remainder with continuous over-and-over sutures. Aortograms were obtained just prior to sacrificing the animals in four dogs (611, 674, 659, 618) 200, 230, 265, and 310 days after implantation of graft. All showed a satisfactory aortic pathway (Fig. 1).

TABLE I. OBSERVATIONS WITH THE USE OF GRAFTS MADE OF TWO LAYERS OF NYLON FUSED TO ONE LAYER OF POLYTHENE

NUMBER OF ANIMAL	LENGTH OF GRAFT (CM.)	DIAMETER OF GRAFT (CM.)	LOCATION OF GRAFT	TYPE OF SUTURE	PERIOD OF OBSERVATION (DAYS)	PATENCY OF GRAFT
606	5	1	A	C	231	+
611	5.3	1	A	C	200	+
618	10	1	A	C	310	+
636	8	1	A	C	69	+
648	7.5	1	A	C	124	+
619	10.8	1	T	C	92	+
624	10	1	T	C	7	+
637	8.1	1	T	C	2	0
644	8.5	1	T	C	14	+
649	8.5	1	T	C	7	+
659	8	1	T	C	265	+
674	7.7	1	T	C	230	+
855	6	1	T	E	3	+
856	6	1	T	E	20	+
858	6	1	T	E	10	+
863	6.5	1	T	E	34	+
887	6	1	T	E	13	+
623	7	0.8	A	C	2	0
629	7.5	0.8	A	E	1	0
642	5.5	0.8	A	C	131	+
654	4.8	0.8	A	C	138	+
655	6.9	0.8	A	C	35	0
663	5.2	0.6	A	C	162	+
693	4.8	0.6	A	C	114	+
857	6	0.8	T	E	2	0
874	6	0.8	T	E	1	+
875	6	0.8	T	E	29	+

In ten animals smaller grafts were used. Two had a diameter of 0.6 cm. and eight a diameter of 0.8 cm. These grafts varied in length from 4.8 to 7.5 cm., and averaged 6 cm. in length. They were in place from one to 162 days. In four animals the interval between insertion of the graft and post-mortem study was 114 days or longer. The graft remained patent and functioned well in six of the ten animals, while in four thrombosis occurred. In the four animals in which thrombosis took place the operator felt that interposition of the graft had been accomplished in a technically satisfactory manner. An aortogram was made prior to sacrificing the animal with the graft of longest duration (654). A good aortic pathway without constriction or dilatation was demonstrated.

Immediately after insertion of the grafts and release of the occluding clamps, they were seen to fill with blood and to transmit a pulsatile flow into

the distal aorta. Occasionally a small transient leak was noted in some portion of the line of anastamosis; often there was no leak. In all, the field was soon dry, and no significant blood loss occurred in any. When examined a few weeks after implantation, the outer surface of the plastic graft was covered by a new fibrous layer. This became better differentiated with the passage of time (Fig. 2). The thickness of this new aortic wall changed little from two weeks to eight months or more (Fig. 3). Within one day after implantation the inner portion of the graft became lined with a smooth fibrin layer (Fig. 4). After a time, the lining membrane became organized into fibrous tissue (Fig. 5). Although this process became complete in some, in other

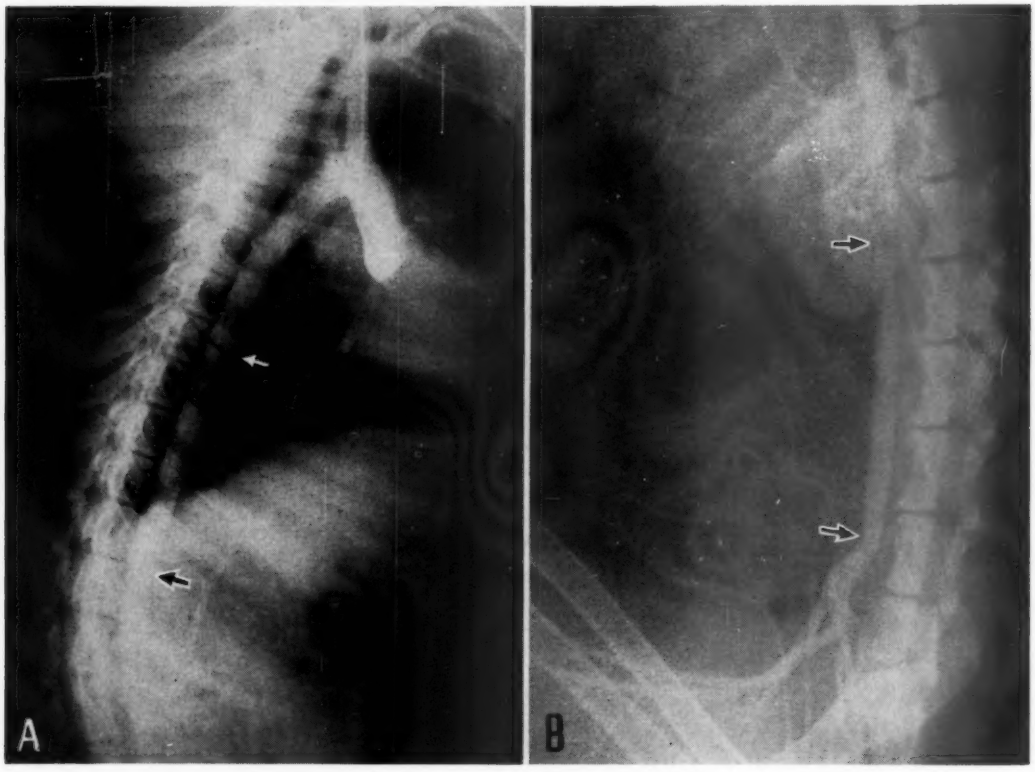

Fig. 1.—Aortagrams in dogs with nylon-polythene aortic grafts. *A*, Dog 674. Length of graft 7.7 cm. Age 230 days. *B*, Dog 618. Length of graft 10 cm. Age 310 days. The grafts are seen to be widely patent, without constriction or dilatation.

specimens approximately six months in age portions toward the center of the graft were still covered only by unorganized fibrin. The fibrous layer on the interior of the graft was intimately adherent to the nylon fibers and grew in between the two layers of nylon and the layer of polythene (Fig. 5, *C*). With passage of time two distinct layers of this inner fibrous tissue were evident, that nearest the plastic cloth being less cellular and less dense than the other. In at least those areas which grossly had the smooth appearance of the normal aorta, the lining membrane was true endothelium (Fig. 5, *D*). In one specimen 265 days old a calcium plaque near the line of anastamosis and in

the inner fibrous layer was seen (Fig. 5, *E*). Calcification was not noted in other specimens. The new adventitial layer outside the plastic graft tended to be composed of less dense fibrous tissue than that on the interior.

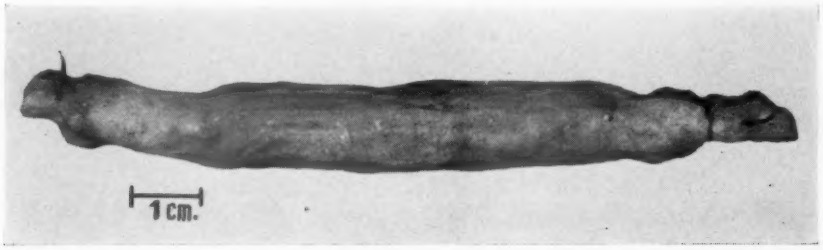

Fig. 2.—Photograph of nylon-polythene graft 265 days after implantation. The graft and a short segment of aorta above and below have been distended by intraluminal injection after ligation of the ends (659).

Fig. 3.—Photographs of cross sections of nylon-polythene grafts cut through the mid-portion of the grafts after distention and fixation with formalin (659, 674, 863, 875, 887). From left to right the age of the grafts is 265, 230, 34, 29, and 13 days. The thickness of the wall changes little with the passage of time. In transsecting the specimens some separation of the layers about the plastic material inadvertently took place.

OBSERVATIONS WITH LUCITE-COATED NYLON GRAFTS

Grafts of Lucite-coated nylon were placed in the aortas of forty-one dogs. Thirteen of them were 1 cm. in diameter and all of these were placed in the thoracic aorta. They varied in length from 5 to 9.2 cm. and averaged 6.3 cm. in length. They were examined from one to 184 days after implantation. In only three animals was the interval between operation and post-mortem examination greater than two months. One was six months old. The grafts remained patent in all but one animal (760). In the exceptional animal the interpolation of the graft was thought to have been satisfactory. In one additional animal (817), death occurred on the fourteenth postoperative day. There was free blood in the pleural cavity and an extensive clot around the graft. The suture lines were intact and it is possible that bleeding had occurred through the graft, although no gross defect could be observed. Of the remaining eleven animals a satisfactory aortic pathway was maintained in ten, while in one (837) marked narrowing was observed at the time the animal was sacrificed on the seventy-second day after implantation. In this case an aortagram made just beforehand revealed moderate reduction in the caliber of the grafted section. Aortograms in two other dogs (700, 751) showed no de-

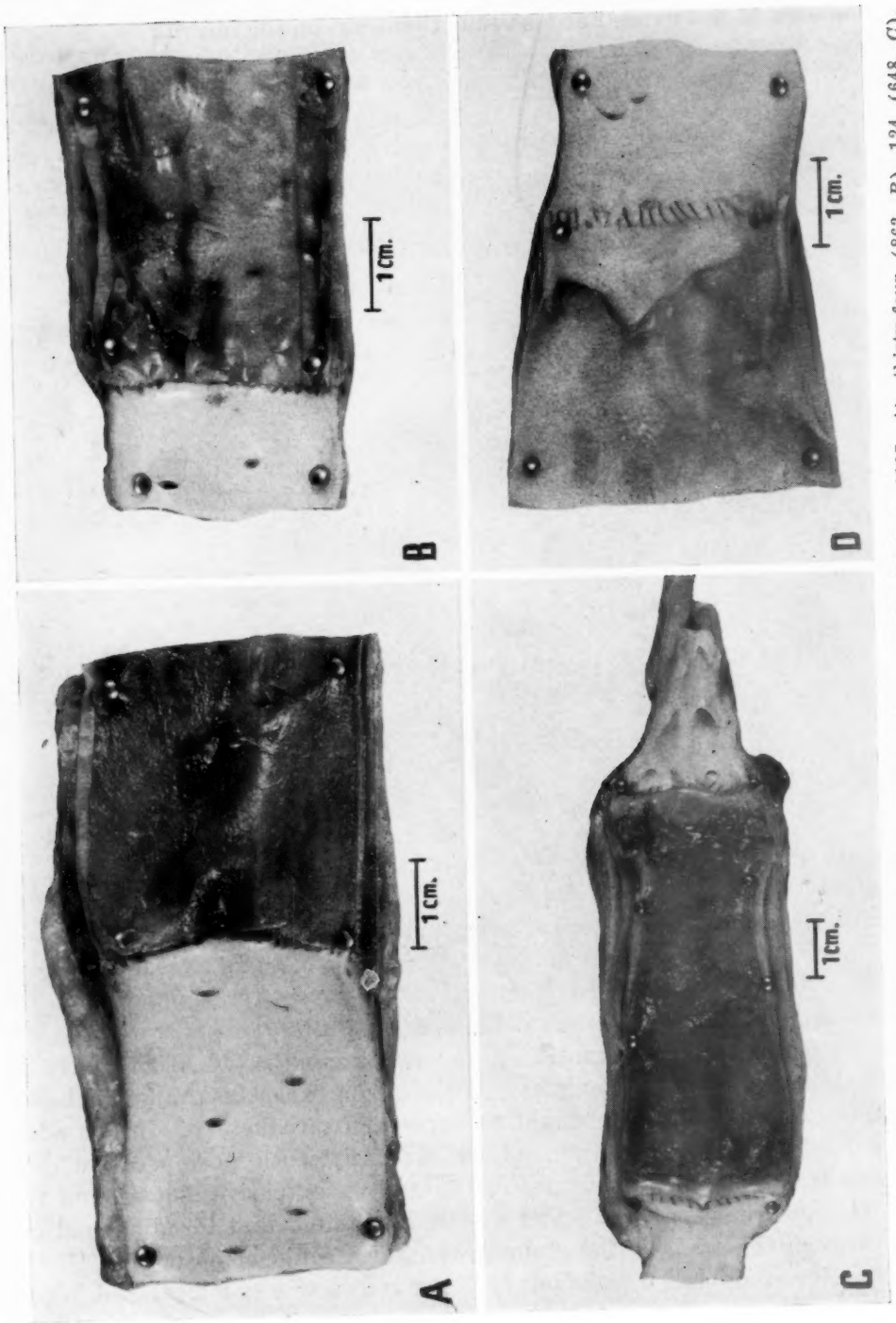

Fig. 4.—Photographs of the interior of nylon-polythene grafts thirteen (887, *A*), thirty-four (863, *B*), 124 (648, *C*), and 265 (659, *D*) days after implantation. These grafts were, respectively, 6, 6.5, 7.5, and 8 cm. long. In the older specimens growth of an endothelial layer from the line of anastamosis toward the center of the graft is seen.

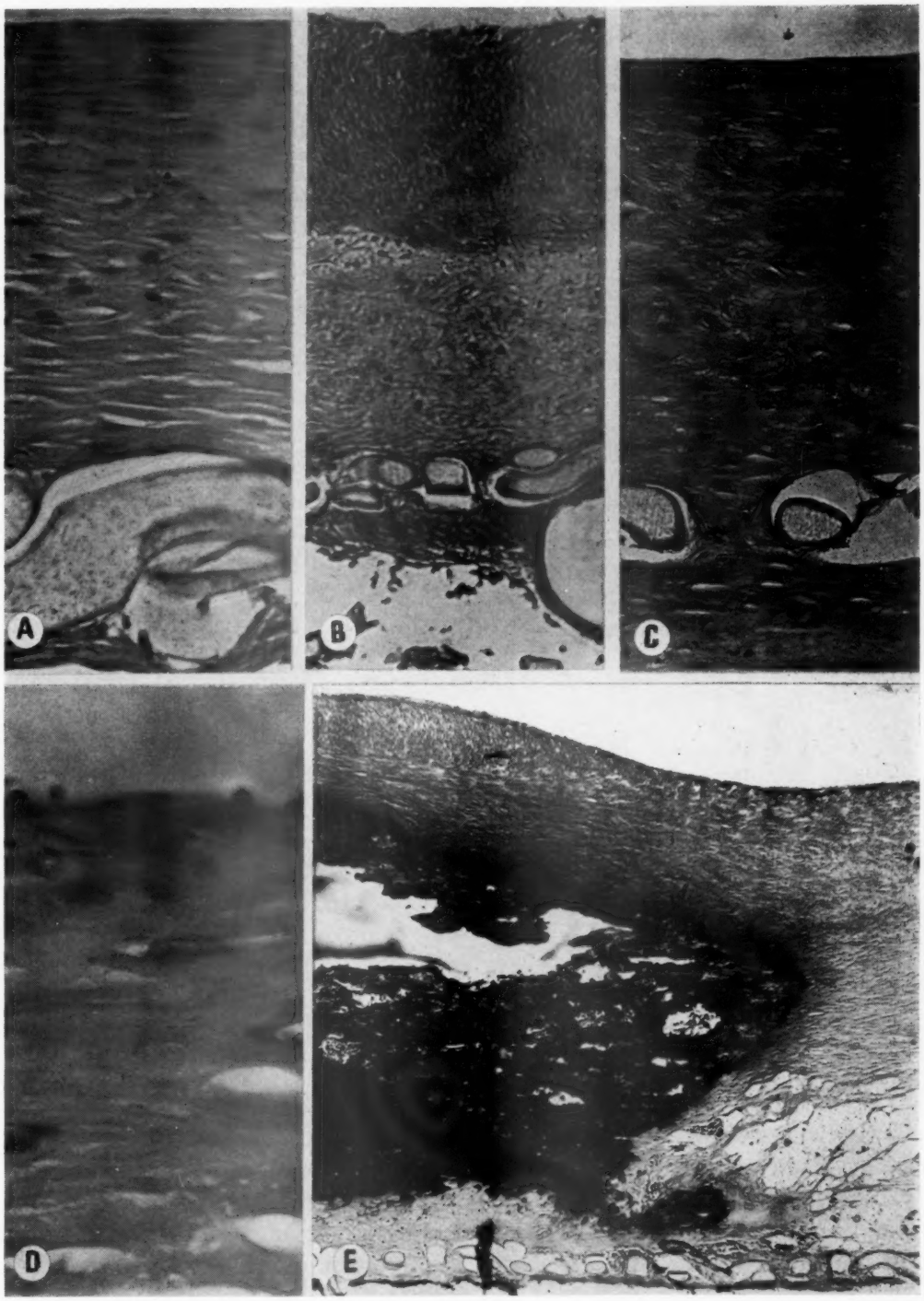

Fig. 5.—Photomicrographs of hematoxylin and eosin stained sections of the nylon-polythene grafts. *A*, Dog 619. Age ninety-two days. *B*, Dog 654. Age 138 days. *C* and *D*, Dog 618. Age 310 days. *E*, Dog 659. Age 265 days. The open spaces about the plastic material are artifacts due to difficulty in sectioning or to shrinkage. The external or adventitial fibrous layer is not shown in any photomicrograph.

formity 185 and fourteen days after insertion of the graft. In six of the thirteen animals, everting sutures were used and in seven, continuous over-and-over sutures.

TABLE II. OBSERVATIONS WITH GRAFTS MADE OF NYLON COATED WITH LUCITE

NUMBER OF ANIMAL	LENGTH OF GRAFT (CM.)	DIAMETER OF GRAFT (CM.)	LOCATION OF GRAFT	TYPE OF SUTURE	PERIOD OF OBSERVATION (DAYS)	CONSTRICTION OF GRAFT	PATENCY OF GRAFT
681	9.2	1	T	E	4	0	+
700	6.3	1	T	C	185	0	+
705	6.2	1	T	C	14	0	+
706	7	1	T	C	4	0	+
750	5.5	1	T	C	62	0	+
751	5	1	T	C	14	0	+
759	6	1	T	C	10	0	+
760	6	1	T	C	1		0
773	6	1	T	E	1	0	+
817	6	1	T	E	14	0	+
819	6.4	1	T	E	37	0	+
837	6.5	1	T	E	72	+	+
848	6	1	T	E	1	0	+
684	7	0.8	T	C	200	+	+
699	5.6	0.8	T	C	3	0	+
727	6	0.6	T	C	3		0
740	5	0.8	T	C	14	+	+
741	5	0.8	T	C	4	+	+
774	6	0.8	T	E	45	0	+
775	6	0.8	T	E	-	-	-
787	5.5	0.8	T	E	112	+	+
799	5	0.8	T	E	103	+	+
800	6	0.8	T	E	1		0
818	6	0.8	T	E	1		0
828	6.5	0.8	T	E	1		0
846	6.5	0.8	T	E	1	0	+
849	6	0.8	T	E	40	0	+
852	6	0.8	T	E	-	-	-
688	4.6	0.8	A	C	8		0
716	4.5	0.8	A	C	93	0	+
717	5.5	0.6	A	C	5	0	+
724	5.2	0.8	A	E	155	0	+
736	4	0.6	A	E	10	0	+
739	6	0.6	A	E	-	-	-
749	7	0.6	A	E	1	0	+
762	6	0.6	A	E	124		0
763	6	0.6	A	E	62	0	+
767	6	0.6	A	E	7		0
770	5.5	0.6	A	E	7		0
771	5	0.6	A	E	124	+	+
772	6	0.8	A	E	125	0	+

In twenty-eight animals smaller grafts were interpolated. Ten were 0.6 cm. in diameter and eighteen, 0.8 cm. The interval between operation and post-mortem examination ranged from one to 200 days. Three dogs with functionally patent grafts several weeks after implantation were subsequently lost and the ultimate fate of these grafts is unknown. Of the twenty-five grafts examined, seventeen were patent and eight occluded. Nine were in place two months or more. Technical difficulties with the suture were encountered in two animals (717 and 800); thrombosis occurred in one but not in the other. In two animals (767, 770) extensive *Clostridium welchii* infection occurred in-

volving the trunk and lower extremities and including the region about the graft. In both of them there was thrombosis of the graft. In a number of animals (684, 724, 740, 771, 787, 799) with patent grafts the aortic pathway was narrowed and in most of them markedly. Aortograms were obtained in five animals (684, 724, 762, 771, 787) prior to the time of their sacrifice 200, 155, 124, 124, and 112 days after implantation. One animal studied 124 days after insertion of the graft had complete obliteration of the lumen (762), while another graft of the same age showed only slight narrowing (771). Of the other three animals examined by aortography, one showed buckling of the graft with

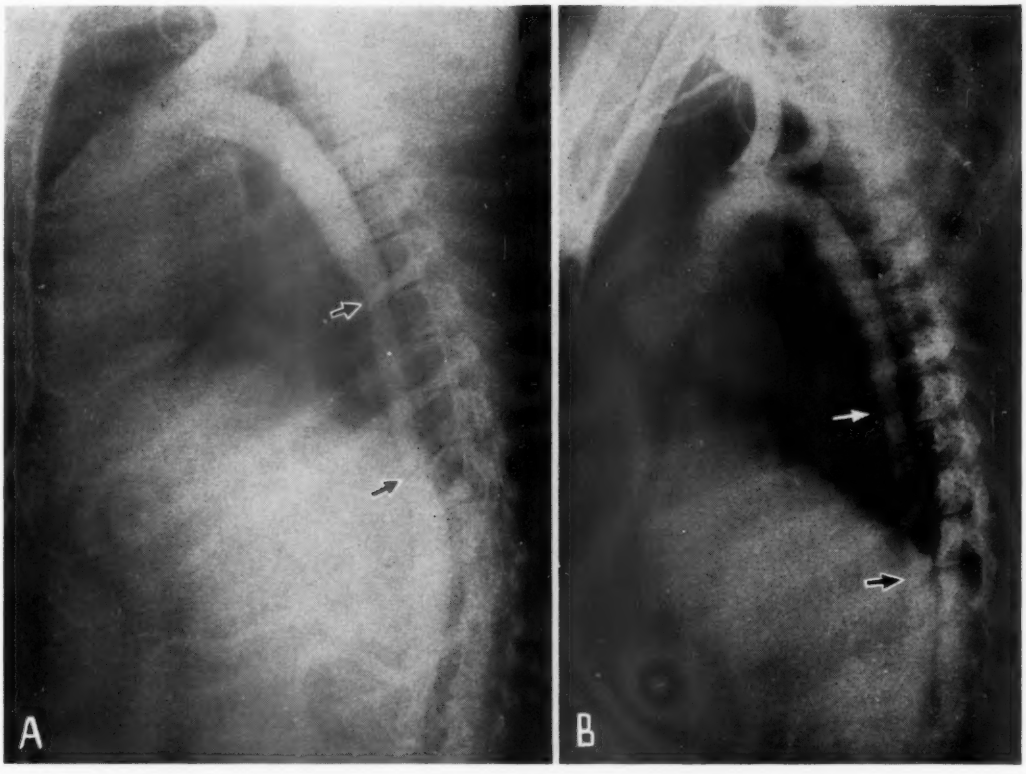

Fig. 6.—Aortograms in animals with Lucite-coated nylon grafts. *A*, Dog 837. Age of graft seventy-two days. Length 6.5 cm. Moderate reduction in lumen is noted. *B*, Dog 700. Age of graft 185 days. Length 6.5 cm. Normal luminal caliber has been maintained.

adequate lumen (724) and two marked narrowing of the lumen in the grafted area. Thus, of all twenty-eight animals with small Lucite-coated nylon grafts, complete thrombosis was observed in eight, in two of which extensive gas infection might be implicated as the cause. Narrowing of the lumen was observed in six additional animals. This was the case in one, fourteen days after implantation (740), and in five grafts varying in age from 103 to 200 days. All the patent grafts of shorter duration except the one mentioned were in good condition and had an adequate lumen.

Immediately after interpolation of the grafts they looked quite similar to those made of nylon and polythene. They early developed a smooth inner

lining of fibrin which grossly and microscopically resembled that seen in the other grafts (Fig. 7). With the passage of time, fibrous organization and endothelization tended to take place. As with the nylon-polythene grafts the rapidity and completeness with which this occurred was variable. For example, the entire lining membrane was well organized in one specimen 125 days old (772), while in another 185 days old the inner layer was almost entirely fibrinous (700). As has been mentioned, many of the grafts remained patent, showed no reduction in lumen, and the thickness of the new fibrous

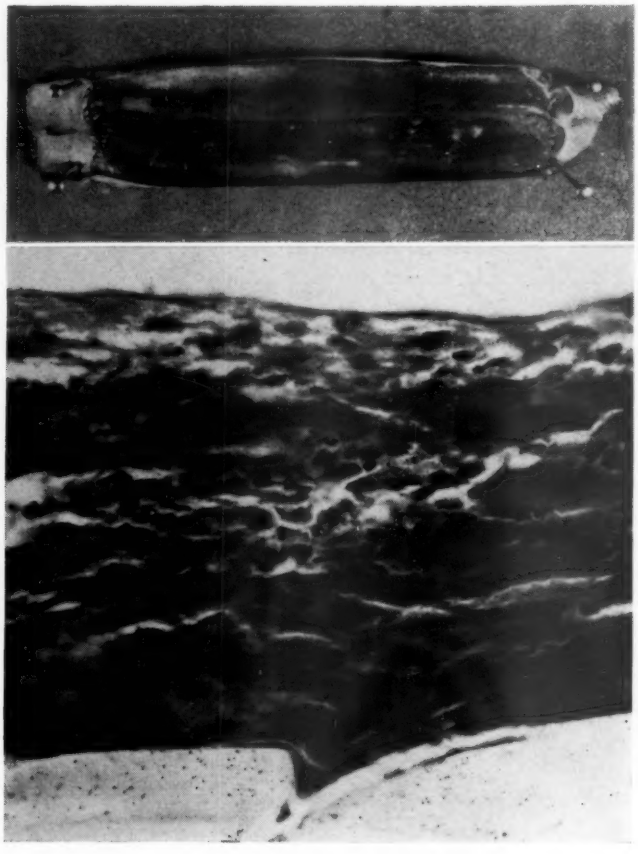

Fig. 7.—Photograph of inner aspect of Lucite-coated nylon graft one day after implantation and photomicrograph of same specimen showing inner layer of fibrin (749).

aorta was similar to that observed with nylon-polythene grafts. In some, however, an entirely different situation was encountered. The graft was found to be surrounded by a layer of relatively fresh clot outside of which was a thick layer of fibrous tissue. Such findings were observed in the one animal in which there was obvious buckling of the graft and in the six in which narrowing of the lumen was observed. This undesirable end result was noted in one animal fourteen days after implantation and in six ranging in age from 103 to 200 days. Cross-sectional views of patent and thrombosed grafts, the external appearance, and the open specimen are shown in Fig. 8.

DISCUSSION

Experiences to date with grafts made by heat fusion of two layers of thin finely woven nylon with a thin polythene membrane interposed between are altogether relatively satisfactory when grafts 1 cm. in diameter are used. Fourteen such grafts, ranging in length from 6 to 10.8 cm., and sutured in

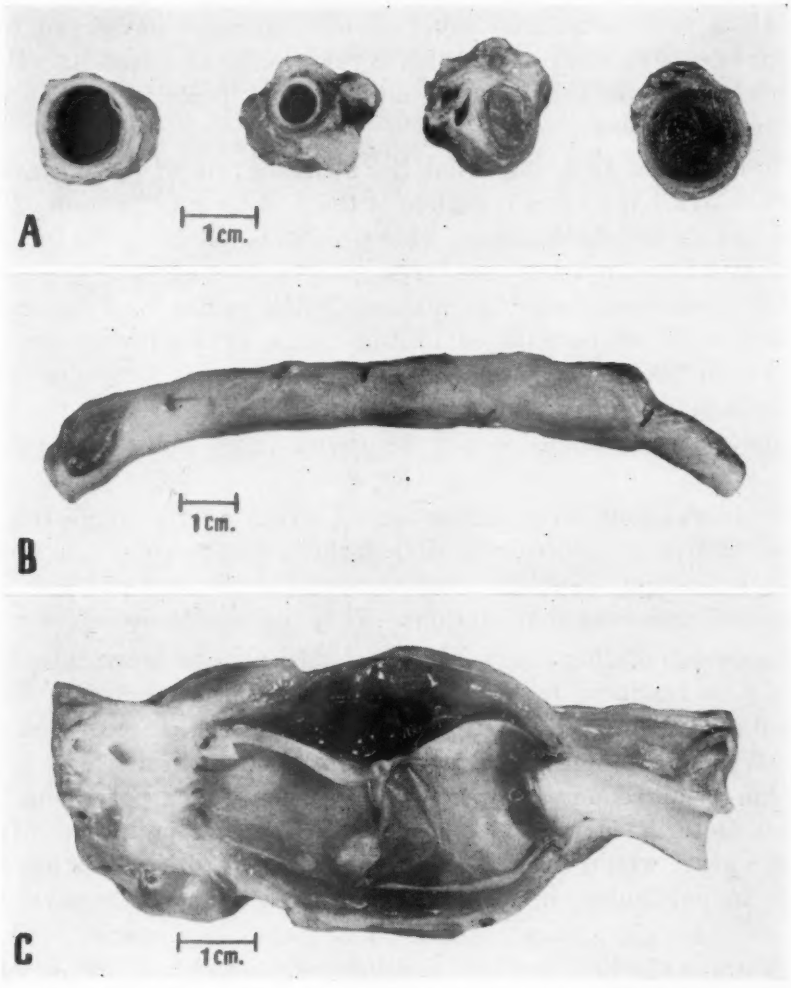

Fig. 8.—Photographs of Lucite-coated nylon grafts. *A*, Cross-sectional views of the mid-portion of four grafts (700, 772, 767, 799). The lumen is unobstructed in two specimens 185 and 125 days after implantation. There is complete thrombosis in one graft seven days old. In the other specimen 103 days after implantation a large clot is interposed between the graft and the outer fibrous wall with resultant marked narrowing of the lumen. *B*, External appearance of graft 200 days old (684). In spite of the relatively normal appearance, marked constriction of the lumen resulted from interposition of a clot between the plastic graft and the external fibrous layer. *C*, Opened specimen 155 days after implantation (724). The plastic graft has remained patent but is buckled. There is a layer of thrombus between the graft and the outer fibrous layer.

place in a technically satisfactory manner, remained patent and showed no narrowing or dilatation over periods up to 310 days. They early became lined with a relatively smooth layer of fibrin. With the passage of time, portions or all of this inner membrane was replaced by organized fibrous tissue, the inner layer of which was denser and more cellular than that adjacent to the

plastic material. This fibrous organization was not complete in some specimens even months after implantation, and in general took place earlier near the ends than in the center of the graft. In older specimens true endothelization was noted, obviously spreading across the suture line from the host aorta toward the middle of the graft. In a single specimen 265 days old a plaque of calcium covered by fibrous tissue and endothelium was observed. Outside the plastic graft a new adventitial layer of fibrous tissue developed early. No tendency to excessive thickness of this layer was noted. Results with smaller grafts were less satisfactory since thrombosis took place in four of ten grafts 0.6 or 0.8 cm. in diameter.

It is unknown at this time what the ultimate fate of these grafts will be. The older the graft the more complete is the fibrous organization of the inner membrane and its endothelization. This process is not complete in some specimens months after implantation. The progression of this general process with age, however, suggests that ultimately the grafts tend to become completely lined with well-organized fibrous tissue covered with smooth endothelium. In the present study no degenerative changes were observed except for the single plaque of calcium in one animal. Whether with the passage of years degenerative changes would be encountered more commonly is not known.

Early observations with Lucite-coated nylon grafts suggested that this material served in an entirely similar fashion to the nylon-polythene membranes. It is evident, however, that as time passes some of these grafts are associated with undesirable alterations. They are obviously inferior.

At the outset of this study it seemed desirable to learn whether plastic cloths could be rendered impervious to blood so as to eliminate the troublesome bleeding encountered when pervious plastic fabrics are used as grafts. In spite of the histologic imperfections observed, grafts 1 cm. in diameter made of thin nylon rendered impervious by fusion with a polythene membrane served satisfactorily over long periods of time. Elimination of bleeding through the graft would seem a worth-while feature since their use in clinical cases and, in particular, in those requiring resection of aneurysms may be attended by a certain amount of blood loss from other sources. The relative merits of various plastics, pervious and impervious to blood, can be established only by further study.

Encouraged by the experimental observations reported, one of us (H. B. S.) has used similar plastic grafts in ten clinical cases of abdominal aortic aneurysms.* All involved the aortic bifurcation and in all but two the aneurysms extended almost to the level of the renal arteries. Two patients died. One was a man who entered the hospital twenty-four hours after rupture of the aneurysm, in shock, and with oliguria. He ultimately died of lower nephron nephrosis. The other fatality was in an elderly patient with a history of two preceding episodes of coronary occlusion and one cerebrovascular accident. The other eight are living and well up to periods of seven months

*The first six of these cases are described elsewhere.[9]

after operative treatment. In nine of the patients nylon-polythene grafts were used and in one a Lucite-coated graft. In all ten patients the grafts functioned well. We know of two additional cases in which these same nylon-polythene grafts were utilized.* One was for replacement of a large aortic aneurysm in a very ill and elderly man who expired four days after operation. The other was interpolated in a successful case of excision for terminal aortic thrombosis. In both cases the grafts functioned well.

It is believed that these experiences indicate that grafts made of fused nylon and polythene can be used successfully as substitutes for the aorta and aortic bifurcation. It is not felt that this particular material will necessarily ultimately prove to be the best plastic for this purpose. It is planned to continue observations of this sort and to compare the results of various plastics, pervious and impervious to blood.

We wish to express our appreciation to Miss Phyllis Brumbaugh and Mrs. Martha Rice for their invaluable technical assistance.

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*These patients were operated upon by Dr. R. P. Lloyd of Fort Wayne, Indiana.

BLOOD VESSEL GRAFTS IN THE TREATMENT OF CHRONIC OCCLUSIVE DISEASE IN THE FEMORAL ARTERY

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INTRODUCTION

THE obstructing lesions of chronic arteriosclerotic arterial insufficiency of the lower extremity may be isolated and discrete and appear in certain characteristic locations such as the lower abdominal aorta, the iliac arteries,[11] and lower third of the superficial femoral artery.[14] This circumstance makes it possible to treat certain cases of chronic arterial insufficiency by surgical restoration of vessel continuity. Recognized by Leriche[12] many years ago, this possibility became an actuality with the development of techniques of thrombendarterectomy by dos Santos[5] and others. Bridging such obstructive defects by means of blood vessel grafts has recently proved more consistently successful.[8] An increasing number of experiences with this method have been reported both in the abdominal aorta and iliac arteries[1, 2, 4, 16] and in the smaller major arteries between groin and knee.[6, 10, 18]

Arteriosclerotic obstruction is far more common in the femoral artery than in the more proximal arteries in the pelvis and abdomen,[11, 14] and the incidence of technical problems and failure is greater in operations on the smaller femoral artery than on the iliac artery or aorta according to experience at the Massachusetts General Hospital. For these reasons, only occlusive disease in the femoral and popliteal arteries will be considered in this report.

CLINICAL MATERIAL

All patients entering the surgical wards of the Massachusetts General Hospital with complaints referable to chronic arterial insufficiency of the lower extremity were screened and arteriography was performed if obstruction above the popliteal artery was suggested by an absent popliteal pulse. Patients were considered possible candidates for grafting if arteriography showed a segmental obstruction technically feasible to by-pass. A patent major artery of adequate caliber below the block and above the popliteal bifurcation was the chief requirement. Extensive occlusive disease in the proximal superficial femoral artery did not constitute a contraindication to graft since it has been possible to handle complete occlusion of this artery by proximal endarterectomy at its origin or by end-to-side anastomosis with the parent artery.

This work was supported in part by a research grant from the National Heart Institute, United States Public Health Service.

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About one-quarter of the patients with a clinical diagnosis of femoral artery occlusion proved on arteriography to have a segmental femoral artery block, and slightly more than one-half of these were grafted.

Cases were divided into two main groups according to the degree of ischemia present, the first group including those with intermittent claudication and adequate circulation at rest; the second group including those with severe ischemia threatening amputation by virtue of ischemic lesions or unbearable pain. These two groups differed in their indication for operation.

Arterial graft was recommended in the first group if the claudication was truly disabling and if there were not associated diseases making the risk of elective surgery too great. Angina pectoris was considered a contraindication primarily because it limited the increase in ambulation potentially available from operation. A healed, asymptomatic, myocardial infarct was not considered a contraindication.

All patients in the second group with an operable segmental block were recommended for arterial graft. Inasmuch as arterial graft is performed as an alternative to amputation in these patients, an operative risk considerably greater than in the first group is acceptable.

Twenty-two extremities of twenty-one patients were operated on in this series. Eight patients were in the first group and had an average age of 51. Thirteen patients were in the second group and had an average age of 63, with six patients in their seventies.

OPERATIVE TECHNIQUE

The technique of operation is being constantly improved and modified and cannot be considered standardized, but the following generalizations apply:

The graft is planned to by-pass, if possible, not only the occluded artery but also all points of narrowing because of the possibility of later thrombosis occurring in such regions. The extent of dissection in the thigh is minimized since it appears to be related to the late postoperative morbidity in these patients. Only in short obstructions of 15 cm. or less is the entire segment of occluded vessel exposed and resected. Where the obstruction is longer, the operation is performed through two separate incisions over the upper and lower ends of the diseased vessel, and the occluded segment is not resected. The graft is drawn through Hunter's canal between the two incisions and end-to-end anastomosis performed at points of minimal sclerosis as determined by palpation and section of the artery. Where exposure of both groin and popliteal space is required, it is convenient to place the patient in a lateral position with the diseased leg down and the upper leg draped so that it can be moved.

Interrupted everting mattress sutures of 00000 Deknatel are used in the anastomosis. Stay sutures are not necessarily used, but the more difficult sutures in the region of atheromata are placed first. The number of sutures used is minimized so that expansion of the vessel at the anastomosis will not be limited when the clamps are released. Soft bulldog clamps are used, and

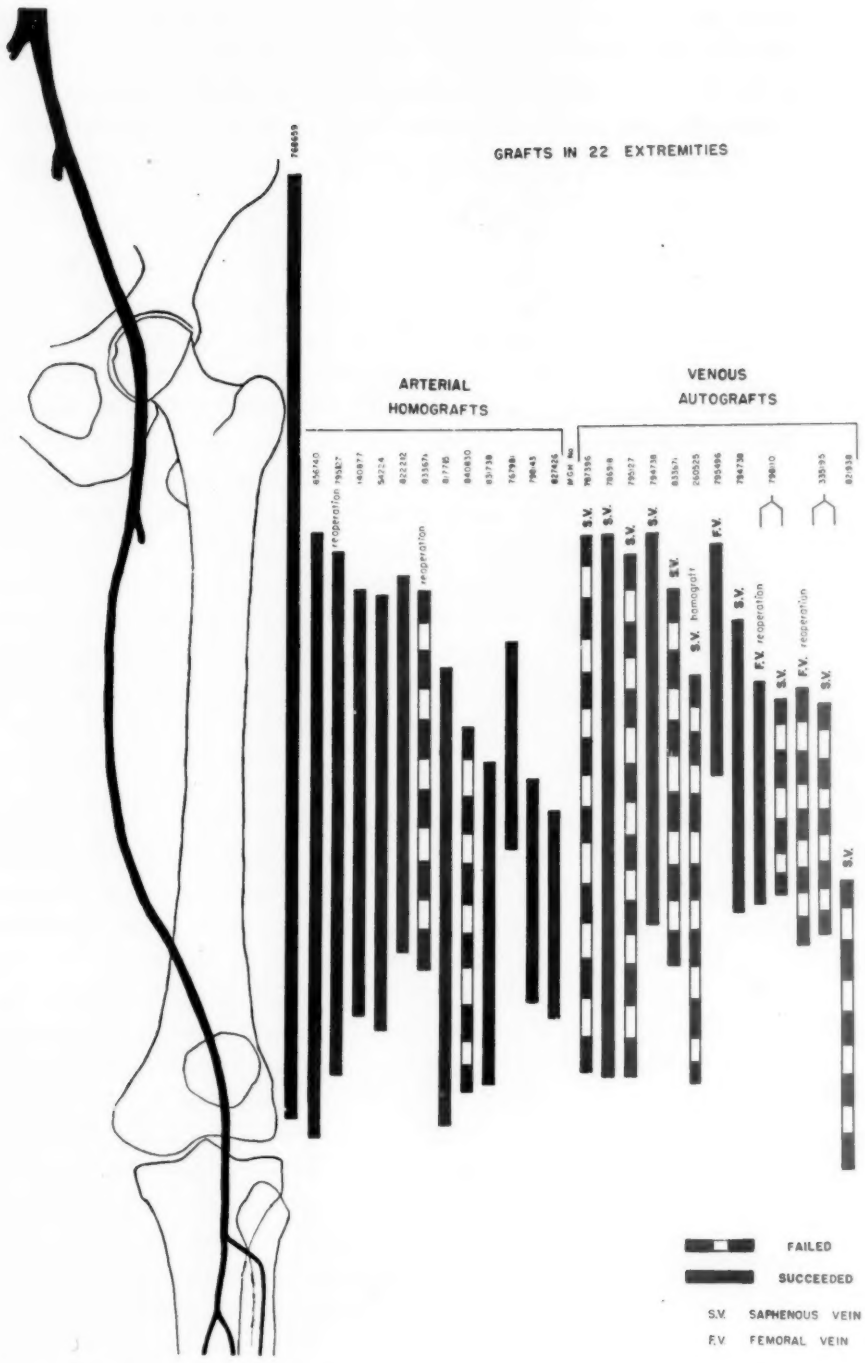

Fig. 1.—Graphic representation of the location, length, and result of thirteen arterial homografts and thirteen venous autografts in twenty-two extremities. Four patients were reoperated on in the immediate postoperative period for removal of a thrombosed graft and insertion of a new graft. It will be noted that the incidence of success was far greater in the arterial than the venous grafts.

dilute heparin solution is injected into the host vessel beyond them in order to avoid thrombosis in the arrested column of blood. For the same reason, clamps are not reapplied after they are released, hemostasis being secured at the anastomosis by gentle pressure or a few interrupted sutures if natural hemostatic mechanisms prove ineffective.

Fresh venous autografts or femoral artery homografts preserved by the freezing-irradiation technique of Meeker and Gross[15] have been used in this series. A frozen venous homograft was used in one case.

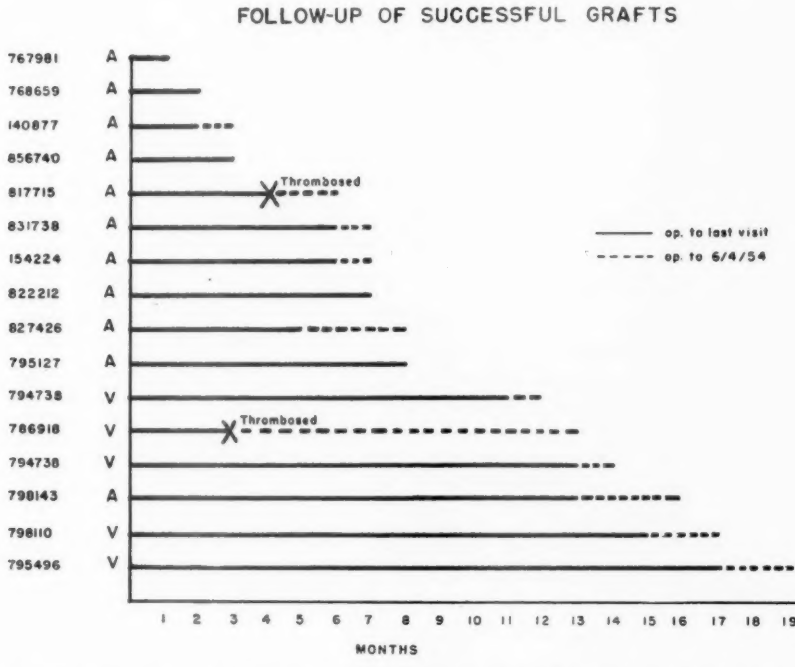

Fig. 2.—The length of follow-up of the sixteen successful grafts. The two patients with late occlusion of the graft are shown here. Arterial homografts and venous autografts are differentiated by the letter *A* or *V* to the left of the figure.

RESULTS

Fig. 1 summarizes the location, length, and result in the grafts used. Twenty-two extremities in twenty-one patients were grafted. Sixteen grafts were successful in that patients left the hospital with functioning grafts proved by the appearance and persistence of peripheral pulses or by arteriography. Four patients were reoperated on within twenty-four hours of the original grafting because of thrombosis, and a new graft inserted. There was a successful result in two of these cases.

Better results in the arterial than in the venous grafts are apparent in Fig. 1. Immediate postoperative thrombosis occurred in eight of thirteen venous grafts, including the one frozen venous homograft. In one case (335195), a thrombosed saphenous autograft was replaced by a femoral venous autograft with immediate and severe obstruction to venous return from the leg and thrombosis of the second graft.

There were two immediate failures in thirteen arterial homografts. In one case failure resulted from sepsis (833671). In the other (840830), thrombosis is thought to have resulted from severe occlusive disease in the popliteal artery and beyond (Fig. 4).

Fig. 2 shows the follow-up in the successful cases. Patency of the graft at follow-up was determined by examination of peripheral pulses and by oscillometry. One patient had persistence of a pedal pulse after late thrombosis, but there was a considerable decrease in the volume of the pulse, and oscillometric studies of calf and thigh revealed a reversion to the preoperative status.

There were ten successful grafts in nine patients with a complaint of intermittent claudication, including three who had additional ischemic lesions. All patients were relieved of claudication following operation. Two patients had recurrence of claudication following late occlusion of the graft. All claudicating patients were tested postoperatively by walking up to one mile at 120 steps per minute under observation. With the exception of one patient who had an occluded graft at the time of the test, none had intermittent claudication in the operated extremity. Five patients, however, were unable to complete the distance because of shortness of breath, angina, general fatigue, or contralateral claudication.

The nine patients with ischemic lesions and a successful graft had immediate relief of ischemic pain and rapid inauguration of healing. Two patients with ischemic ulceration were successfully skin-grafted. One patient with wet gangrene of a toe had an open amputation of the toe, which healed. The remaining six healed their lesions without further surgery.

The longest graft extended from the origin of the external iliac artery to the popliteal artery. This case is reported here:

CASE REPORT

M. G. H., No. 768659, a 59-year-old diabetic woman, entered the hospital for treatment of painful ulcerations of the left leg of seven months' duration. Seven months prior to admission, ligation and stripping of varicose veins of the left leg had been performed elsewhere. She had noted intermittent claudication of the left calf before this operation was performed. Following operation the incisions below the knee had broken down and remained ulcerated to the time of admission, and in addition she had developed a painful lesion of the left heel. She had been bedridden and suffered from pain at rest. Local therapy had been of no avail.

The patient had had hypertension for twenty years, angina pectoris for eight years, and a cerebrovascular accident with residual partial paralysis of the right leg for five years in addition to mild diabetes controlled by diet.

Blood pressure was 280/120 with moderate cardiac enlargement but no signs of cardiac failure. No pulses were palpable in the legs below the femorals, and the left femoral pulse was weak. There were three dirty, deep ulcerations of the left lower leg ranging in diameter from 3 to 5 cm. There was a 3 cm. black necrotic pressure sore on the point of the left heel.

Arteriography (Fig. 3) showed segmental obstructions in both the left external iliac and left superficial femoral arteries.

There appeared to be no hope of healing these lesions by conservative measures, and left low thigh amputation in the presence of a partially paralyzed right leg would have

totally immobilized the patient; so in spite of the obviously great surgical risk involved, an attempt was made to restore arterial continuity to the leg. A nineteen-inch femoral-iliac arterial homograft was placed in a tunnel from the external iliac stump to the popliteal artery. Retroperitoneal exposure of the iliac artery and short incisions in the groin and popliteal space were used. Following operation, a dorsal pedal pulse appeared and the ulcerations healed with surprising rapidity. The last lesion to close, the pressure sore on the heel, was epithelized when she was seen six weeks after operation.

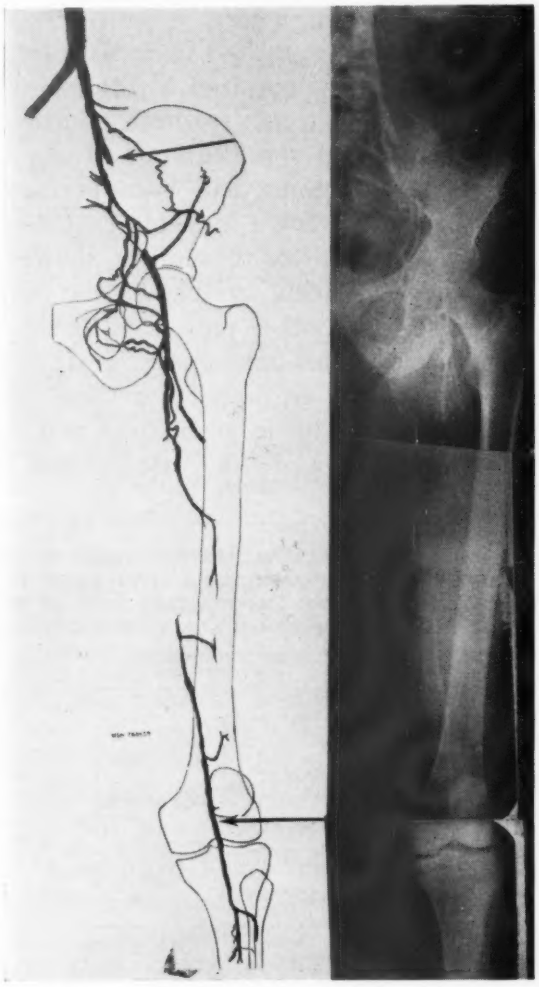

Fig. 3.—Arteriogram in the reported case of iliofemoral graft. An arterial homograft was placed from the stump of the external iliac artery, indicated on the tracing by the upper arrow, to the popliteal artery indicated by the lower arrow.

COMPLICATIONS

Thrombosis and hemorrhage have been the most frequently encountered complications in the immediate postoperative period. Hemorrhage has been less of a problem since postoperative anticoagulant therapy was abandoned early in the series. Thrombosis has occurred despite anticoagulant therapy. When thrombosis of the graft has occurred, it has taken place either in the first few postoperative hours or months later. Early thrombosis has almost always been

related to some mechanical factor limiting flow, such as a poor suture line, hematoma, graft of inadequate caliber, or narrowed artery above or below the graft. An aggressive attitude in re-exploring such patients and remedying the defect has proved worth while.

Sepsis of the graft was encountered in one case and was traceable to an error in the sterilization of the mineral oil then used as a suture lubricant. This case was characterized by repeated major secondary hemorrhages finally requiring ligation of the external iliac artery.

Four patients with ischemic lesions had immediate failure of their grafts. Three of these patients ultimately required low-thigh amputation, and the previously mentioned patient with sepsis required mid-thigh amputation.

Two patients with intermittent claudication had unsuccessful grafts. In both cases preliminary sympathectomy had been performed. The walking tolerance of these two patients is shown in Table I. One patient (821938), a 35-year-old man with primary popliteal thrombosis, showed a considerable increase in walking tolerance following sympathectomy and further increase after his unsuccessful graft. The other patient (260525) also showed slight increase in walking tolerance after his unsuccessful graft. One recalls Leriche's claim of benefit from resection of an occluded arterial segment.[13] However, walking tolerance shows great day-to-day variation,[9] and the only significance of these observations is that failure of the graft did not make these patients appreciably worse.

TABLE I. THE EFFECT OF FAILURE OF A FEMORAL ARTERY GRAFT ON INTERMITTENT CLAUDICATION (IN THE TWO PATIENTS WITH INTERMITTENT CLAUDICATION WHO HAD UNSUCCESSFUL GRAFTS THERE WAS SUBJECTIVE IMPROVEMENT AND, AS SHOWN HERE, NO DECREASE IN WALKING TOLERANCE COULD BE DEMONSTRATED)

	WALKING TOLERANCE = $\frac{\text{DISTANCE TO PAIN (FT.)}}{\text{MAXIMUM TOLERABLE DISTANCE (FT.)}}$ 120 STEPS/MIN.							
PATIENT	DATE	TOLERANCE	LUMBAR SYMPATHECTOMY	DATE	TOLERANCE	UNSUCCESSFUL GRAFT	DATE	TOLERANCE
821938	8/21/53	$\frac{67}{301}$	8/24/53	8/31/53	$\frac{335}{502}$	9/ 4/53	9/12/53	$\frac{469}{603}$
260525			4/14/53	4/22/53	$\frac{268}{536}$	4/25/53	6/ 8/54	$\frac{469}{1876}$

Significant late complications are thrombosis and edema. Thus far two late thromboses of the graft have been encountered. One (817715) occurred five months after operation and was preceded by gradual decrease in the amplitude of foot pulses. An ischemic ulcer, which had healed while the graft was patent, recurred following thrombosis. The other late occlusion (786918) occurred approximately three months postoperatively in a patient with claudication only. This patient reverted to her preoperative symptomatic status.

Postoperative edema of the leg is common, usually coinciding with the increased periods of dependency accompanying increased use of the leg two or three weeks after surgery. This has been treated with elastic support and in most cases has ceased to be a problem after three or four months.

DISCUSSION

In our opinion, greater success can be expected from arterial homografts than from venous autografts. The high failure rate with autografts reported here may in part be due to technical inexperience since most of these operations were performed early in the series before an artery bank was available. However, Julian and associates[10] reported failure in seven of nineteen venous autografts in arteriosclerotic femoral arteries, and Fontaine and co-workers[7] had failure in over one-half of forty venous autografts. It has been apparent at the time of surgery that the flow through a long saphenous vein graft is strikingly less than that through an arterial homograft of equal length in the same patient. In this observation lies an important reason for the inferior performance of the vein grafts.

The immediate results of successful arterial grafts have been extremely gratifying from the viewpoint of both patient and surgeon in cases of intermittent claudication and in cases of ischemic lesions. The ultimate worth of the procedure depends on the late thrombosis rate. Cockett[3] reported late thrombosis in eleven of fourteen successful femoral artery homografts in arteriosclerotic patients, and Rob[17] found thrombosis within one year in four of nine. Warren[19] found occlusion of the graft to occur within six months in two of three femoral arterial homografts and in four of thirteen venous autografts. These are depressing statistics. The late thrombosis rate in the presented series has been somewhat lower, two of sixteen. In these cases an effort was made to be radical in eliminating areas of narrowing as well as areas of occlusion. Follow-up has not yet been long enough to determine whether or not this approach will result in a truly significant lowering of the late thrombosis rate. The observation of Cooke and associates[4] of late thrombosis in two of five homografts performed for traumatic lesions presumably without disease in the adjacent artery suggests that the cause of late occlusion might be sought elsewhere than in associated arteriosclerotic lesions. We feel that the problem of late occlusion will be soluble by technical modifications and ultimately will not detract from the worth of the procedure.

A considerable degree of occlusive disease in the smaller arteries of the low leg is consistent with a successful graft since, in general, occlusion in this region is well compensated by collateral circulation. Thus in the present series over 60 per cent of the patients with successful grafts showed evidence of occlusion of arteries below the popliteal bifurcation in the operated leg by the postoperative absence of one or both pedal pulses. Of course, occlusive disease in the popliteal outflow can be so extensive that flow through the graft is not sufficient to maintain patency. An estimate of the degree of distal disease allowable may be gained from inspection of Fig. 4, which compares the lower leg vessels in two cases in this series, one successful in spite of obstruction in all the major lower leg vessels, and the other a failure because of thrombosis, presumably due to poor popliteal outflow.

Of the twenty-two extremities grafted, eleven had preliminary lumbar sympathectomy. Sympathectomy was performed on the younger good-risk

patients on the presumption that the operation would give protection to the integument when, in years to come, the inevitable progression of their arteriosclerotic occlusive disease occurs. The place of lumbar sympathectomy in such reconstructive surgery is not clear. In cases where the graft remained open there has been no evidence of benefit from sympathectomy. Low-thigh amputation was not avoided in the one patient with gangrene who had sympathectomy

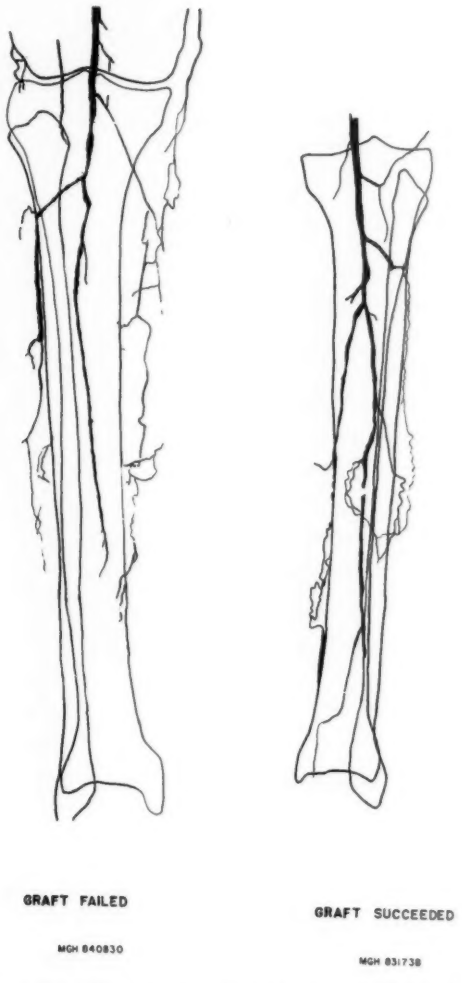

Fig. 4.—The left-hand arteriogram tracing shows distal occlusive disease sufficient to cause thrombosis of a femoral graft. Poor popliteal flow is suggested by the abundant collateral parallel with this vessel.

The right-hand tracing shows occlusion of all three leg vessels, but sufficient collateral to allow good popliteal flow and a successful femoral graft.

before an unsuccessful graft. The two patients with intermittent claudication only and an unsuccessful graft both had preliminary sympathectomy and may have been benefited in that they showed symptomatic improvement as noted in the discussion of complications. The patient with late thrombosis and a recurrent ischemic ulcer might not have had recurrence of his lesion if a sympathectomy had been performed. It is possible to consider sympathectomy as

protection against failure of the graft, but it has its price in morbidity and mortality in the arteriosclerotic patient who tolerates multiple operations poorly. One patient with intermittent claudication was not grafted because of a cerebrovascular accident complicating the preliminary lumbar sympathectomy.

It is of interest that pedal pulses are frequently not palpable until a few days after surgery in these cases. While the concept of the increased arterial pressure in the distal arterial tree gradually "pounding open" narrow vessels is an attractive rationalization of this phenomenon, a more likely explanation lies in the observation of Eastcott[6] that the muscular circulation is greatly increased for several days after a successful femoral graft. Thus blood will follow the path of least resistance through the proximal circulation and not be diverted down to the pedal pulses until normal vascular tonus is restored. Such a disappearance of pulses with increase of the muscular circulation is seen on exercise in many patients with arteriosclerotic narrowed vessels. Severe traumatic arteriospasm is occasionally observed in these patients postoperatively. In a case observed by one of us, apparent total arrest of circulation in the lower leg and foot followed aortic graft. A line of demarcation gradually descended over several days, but irreversible ischemic changes in the forefoot resulted despite the eventual return of bounding dorsal pedal and posterior tibial pulses. In the reported series this complication has been treated by warming the extremity and has not been of more than a few hours' duration. Lumbar paravertebral block has not proved effective in treating this disorder.

SUMMARY

Twenty-two extremities with segmental femoral artery obstruction were treated by blood vessel graft. Operation was successful in sixteen extremities with resulting relief of intermittent claudication and healing of ischemic lesions. The incidence of success was decidedly greater with arterial homografts than with venous autografts. Late thrombosis was observed in one of eleven successful arterial homografts and one of five successful venous autografts.

The indications for, techniques of, and sequelae following this surgery are described.

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ARTERIOSCLEROTIC OCCLUSION OF THE TERMINAL AORTA AND COMMON ILIAC ARTERIES TREATED BY THROMBOENDARTERECTOMY

An Evaluation of the Procedure Based on the Results Obtained in Twenty Cases

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ARTERIOSCLEROSIS is a systemic disorder, but manifestations in a given patient may be restricted to a segment of the arterial tree and remain so for a considerable length of time. It is well known that an individual may recover from an acute coronary thrombosis and survive many years without further manifestations of the disease in the heart or elsewhere. The same protracted course is frequently observed in arteriosclerotic occlusion of large arteries leading to the extremities.

This peculiarity of arteriosclerosis has encouraged many surgeons to search for therapeutic measures directed toward the relief of the arterial obstruction. Attempts in this direction date as far back as 1886 when Severeanu tried the "désoblitération per cathéterisme," followed by the "artériotomies limitées" of Letars in 1902, finally given up in 1905 by Pierre Delbet with the explanation, "They leave behind parietal lesions on which the clot reforms with discouraging rapidity."[1]

Success was finally achieved by dos Santos[2] of Lisbon in 1946, who was fortunate enough to have at his disposal two invaluable tools: angiography and anticoagulants (heparin).

Dos Santos' method, later called thromboendarterectomy, is based on the fact that there is a line of cleavage in the media of the arteriosclerotic artery, between the living outer layer, made up of the adventitia and the outer fibers of the media, and the dead "sequestrum" (Arnulf[3]), comprising the intima and inner portion of the media.

After the first report of dos Santos in 1947, European surgeons started using the method with certain modifications and published several reports with a rather high mortality rate, but with encouraging results in a good percentage of the survivors.[1, 4-9]

In this country there has been little interest in the procedure and only a few reports are to be found.[10-13]

In the belief that the procedure is sound, when the proper indications and correct technique are used, we are presenting our experiences with twenty patients operated on for thrombosis of the terminal aorta and common iliac arteries.

Read at the eighth annual meeting of the Society for Vascular Surgery, San Francisco, June 20, 1954.

TABLE I

PATIENT	SEX AGE (YR.)	VESSELS INVOLVED	OPERATION THROMBOENDARTEREC-TOMY	ANTICOAGULANTS	COMPLICATIONS	FEMORAL PULSES P.O.	RESULT	FOLLOW-UP	MO.
1.	M 54	Occ. Lt. iliac Sten. Term. aorta	Aorta, lt. iliac	IA—8 days Dicou.—6 wk.	0	Present	Good	CVA 1 yr.	39
2.	M 58	Occ. Rt. iliac Sten. Term. aorta	Aorta, rt. iliac Bilat. symp.	IA—5 days Dicou.—6 wk.	Ischemic neuritus Lt. leg	Present	Good	L and W	31
3.	M 46	Occ. Iliacs, aorta, mouth Lt. renal	Aorta, iliacs and lt. renal	IA—1 day IV—3 days Dicou.—2 wk.	Incisional hernia	Present	Good	L and W	29
4.	M 66	Occ. Rt. iliac Sten. Aorta Lt. iliac aneur.	Aorta, iliacs Aneursymorrhaphy	IA—12 hr.	Hemorrhage	—	Death	—	—
5.	M 62	Occ. Rt. iliac Sten. Aorta	Aorta, rt. iliac	IA—5 days Dicou.—2 wk.	Partial ileus 2 mo.	Present	Good	L and W	25
6.	M 45	Sten. Term. aorta	Term. aorta	0	0	Absent	Poor	Not imp.	24
7.	M 51	Occ. Term. aorta and iliacs	Term. aorta, iliacs	IA—3 days IM—1 day Dicou.—1 wk.	0	Present	Good	L and W	23
8.	F 54	Occ. Term. aorta and iliacs	Term. aorta, iliacs	IA—4 days Dicou.—2 wk.	0	Rt. pres. Lt. abs.	Good	L and W	21
9.	M 49	Occ. Rt. iliac Sten. Term. aorta	Term. aorta Rt. iliac Bilat. symp.	IA—1 day IM—5 days Dicou.—2 wk.	0	Present	Good	L and W	19

10.	F 55	Occ.	Term. aorta and iliacs	Term. aorta, iliacs	IA—1 day	Hemorrhage Secondary op.	Present	Good	L and W	19
11.	F 58	Occ. Sten.	Rt. iliac Term. aorta	Term. aorta, Rt. iliac Bilat. symp.	IA—8 days Dicou.—2 wk.	0	Present	Good	L and W	16
12.	F 51	Occ. Sten.	Term. aorta Rt. iliac	Term. aorta, Rt. iliac	IV—1 day IM—1 wk.	Mult. emboli, toes 7th day	Present	Good	L and W	12
13.	M 48	Occ.	Term. aorta and iliacs	Term. aorta, iliacs	IA—5 days Phen.—1 wk.	0	Present	Good	L and W	9
14.	M 45	Occ. Sten.	Lt. iliac Term. aorta	Term. aorta, Lt. iliac	IA—1 day IM—2 days	0	Present	Good	L and W	9
15.	M 45	Occ. Sten.	Term. aorta Lt. iliac	Term. aorta, Lt. iliac Bilat. symp.	IA—5 days Phen.—2 wk.	0	Present	Good	L and W	7
16.	M 46	Occ. aorta, partial to renals	Iliacs,	Aorta up to renals, Iliacs	IA—4 days SC—4 days	0	Present	Good	L and W	6
17.	M 54	Occ. Sten.	Rt. iliac Aorta, lt. iliac	Aorta to lt. renal, Iliacs	IA—3 days Phen.—3 days	0	Present	Good	L and W	4
18.	M 59	Occ. Sten.	Rt. iliac Term. aorta and lt. iliac	Term. aorta, iliacs	IA—2 days Phen.—8 days	0	Present	Good	L and W	3
19.	M 49	Occ. aorta, partial to renals	Iliacs,	Term. aorta, iliacs Rt. lumbar	IA—1 day SC—5 days	0	Lt. pres. Rt. weak	Good	L and W	2
20.	M 60	Occ. aorta, mouth Lt. renal	Iliacs,	Aorta, iliacs and mouth Lt. renal	IA—1 day IM—2 days Phen.—2 wk.	0	Present	Good	L and W	1

Key:
Occ. = occlusion.
Sten. = stenosis.
IA = intra-arterial heparin.
IM = intramuscular heparin.
SC = subcutaneous concentrated heparin.

MATERIAL

In the past three years, we have performed sixty thromboendarterectomies in fifty-eight patients. Of this number, twenty patients had obstruction of the terminal aorta or common iliac arteries. The results obtained in this series form the basis for the present report. A study of the end results of thromboendarterectomy of the external iliac, femoral, and popliteal arteries is planned for a later date. Included with this latter group will be four cases of thrombosis of the aorta down to the femoral arteries.

Table I is a presentation of the data on the twenty patients: 16 patients were men, 4 women. Eight of the patients were under 50 years of age and only three were 60 or over. Three men were only 45 years of age. The four women were between the ages of 51 and 58.

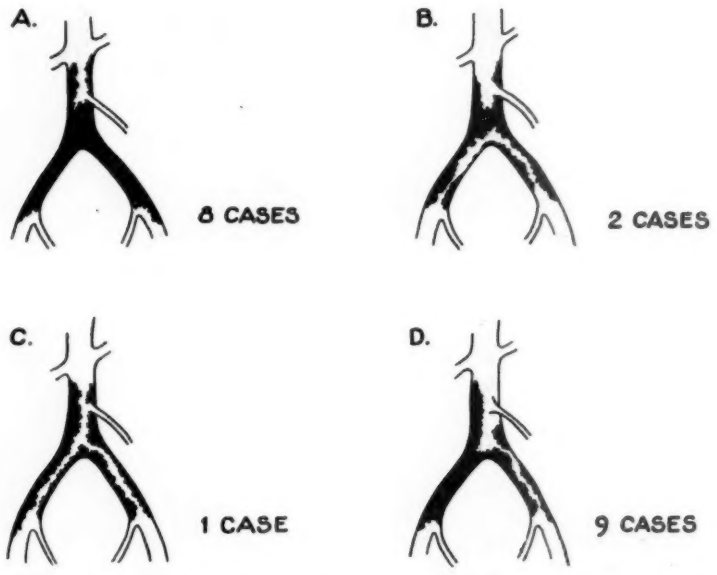

Fig. 1.—Distribution of obliteration in twenty cases of thromboendarterectomy of aorta and iliac arteries.

The final diagnosis made by microscopic examination in all cases was atherosclerosis.

The operative findings are illustrated in Fig. 1.

The clinical picture presented was that of the Leriche syndrome[14] (thrombotic obliteration of the aortic bifurcation) in ten cases (3, 4, 5, 7, 8, 10, 13, 16, 19, 20). Of the remaining patients, seven had complete occlusion of one common iliac with stenosis of the terminal aorta (Cases 1, 2, 9, 11, 14, 17, 18), one had a partial aortic occlusion (Case 6), and two had an aortic occlusion just below the inferior mesenteric artery (12, 15), but with patent iliac arteries.

The following points should be emphasized in the history and physical examination of these patients:

(1) Claudication as stressed by Leriche[14] is frequently atypical. Five patients had pain on walking, three had weakness or fatigue, and twelve had

weakness followed by pain if the exertion was continued. These symptoms affected the hips, thighs, occasionally the calves, and frequently the gluteal area and low back. They were severe, occurring on walking one block or less in all cases.

(2) In the early stages the patient is usually able to start an erection but unable to sustain it. This progresses to complete impotence in most cases. At times it is difficult to elucidate this point because the patient is reluctant to admit it or attributes it to his "getting old."

(3) Decrease in size of the lower limbs is frequently noted by the patient and confirmed on examination.

(4) The usual manifestations of arterial insufficiency at rest, complained of by the patient or found on physical examination, are minimal. In our series only one patient had a necrotic lesion of the foot (Case 1). Only a few complained of cold feet or pallor, and none had rest pain.

(5) In some cases, in spite of the complete aortic occlusion, pulses can be felt in the groin or below, but they are weak and easily compressible. The presence of palpable pulses is due to the extensive collateral circulation some of these patients are able to develop. One of our patients (Case 3) had palpable femoral pulses and visible pulsations in subcutaneous arteries of the abdomen and flanks. The occlusion in this patient extended up the aorta to include partially the left renal artery. He had a typical Goldblatt hypertension. At operation it was possible to remove the arteriosclerotic plaque which partially occluded the left renal artery. The blood pressure postoperatively returned permanently to a normal level (from 230/140 to 120/70—twenty-two-month follow-up).

All these patients were severely incapacitated. Most of them had been forced to abandon their usual occupations, and a few had difficulty even in moving about the house. Three patients had previously been subjected to sympathectomy with little or no improvement.

Aortography by the lumbar percutaneous method first described by dos Santos[16] (1931) was performed in all patients except the patient in Case 3, who had a retrograde left carotid arteriogram with Valsalva maneuver.[17] Forty cubic centimeters of 70 per cent Diodrast or 25 c.c. of Urokon in the same concentration was used after previous sensitivity tests, conjunctival and sublingual for the former and intravenous for the latter solution. A preliminary film was taken to check the position and to look for calcification in the arterial walls. Starting just before injection was completed, six to eight exposures were made with a time interval of approximately one second, using a fast cassette changer.[18] This series of films permitted a clear visualization of the proximal and distal parts of the occlusion and a good study of the collateral circulation. The presence of patent distal arteries was considered essential for the success of the operation. A single film was taken ten minutes later to show the renal function by excretory urography.

TECHNIQUE

Adequate exposure of the involved arteries is essential in order to obtain control of the aorta above the occlusion and of the iliac arteries distally. A rectus retracting, right or left paramedian incision extending from the xiphoid to the pubis was used in all cases.

After systematic exploration of the abdominal organs the small bowel is placed in a plastic bag.[19] The posterior peritoneum is opened directly over the right iliac artery medial to the right ureter, and the dissection is carried out over the aorta to the ligament of Treitz, staying to the right of the inferior mesenteric vein. The aorta and common iliacs are dissected free. The vessels are exposed well above and below the occluded portions, to a point where the arterial wall feels relatively soft and free of gross atheromatous plaques. The larger branches are surrounded by segments of rubber tubing and the smaller by rubber bands.

Suitable clamps are applied just distal to the occluded area. A longitudinal incision is made with the scalpel through the arterial wall down into the occluding material and into the patent lumen of the distal vessel. At this point a polyethylene tube is inserted downward through the incision, and a drip of heparin solution (50 mg., in 250 c.c. of normal saline solution) is maintained at a rate of 20 drops per minute.

The "sequestrum" is shelled out, starting from below and extending the longitudinal incision of the arterial wall upward as necessary. Frequently, atheromatous plaques have to be removed from the orifices of the internal and external iliac arteries. The inferior mesenteric, if patent, is preserved whenever possible. If a sclerotic plaque extends out into this branch, it is removed with a small curette until back bleeding is obtained. Heparin solution is injected into this branch and the occlusion reapplied.

Before the upper limit of the occlusion is reached, a special nonerushing aorta clamp is applied as far above it as possible. The removal of the diseased lining is continued until a relatively good arterial wall is reached. If plaques are found to extend to the renal arteries or above, temporary hemostasis above them is made by pressure on the aorta against the vertebra with a sponge stick temporarily loosening the special aorta clamp. The atheromatous plaques are then removed with forceps or a curette. This was done on four occasions (Cases 3, 16, 19, and 20), thus relieving a partial occlusion of the left renal artery in one patient. The pressure on the sponge stick is momentarily released once or twice to make sure that any loose plaques or thrombi are washed out, the clamp is reapplied, and heparin solution is injected through a hypodermic needle into the aorta above the clamp.

The proximal and distal ends of the dissection frequently have to be in areas where plaques are still present. We prefer to divide the thickened lining obliquely and tack down the edge of the plaque with one or two stitches of 00000 Deknatel. The needle enters the lumen of the artery through the denuded portion and passes out again through the thickened lining. The stitch

can then be tied on the outside of the vessel. This maneuver prevents elevation of the plaque with possible subsequent thrombosis of the vessel.

The vessels are closed with an over-and-over stitch of 00000 Deknatel braided silk. Just before closure, back bleeding from the distal branches is allowed by temporary release of the occluding clamps or rubber bands, and the denuded portion is irrigated with heparin solution.

After the vessel has been closed, a segment of polyethylene tubing with an internal diameter of 0.058 cm. (0.023 inch) and an external diameter of 0.096 cm. (0.038 inch) is inserted into the proximal artery above the upper clamp. This tubing, which is quite flexible, can be introduced through a thin-walled 18 gauge needle (Bishop). A figure-of-eight suture of 00000 Deknatel braided silk should previously have been placed, and the needle inserted through the middle of this suture. As soon as the tubing is well within the lumen of the artery, which will become evident from the appearance of arterial blood in the polyethylene tubing, the needle is withdrawn, leaving the tubing within the artery. A 22 gauge needle is then inserted into the proximal end of the tubing and connected to a syringe containing the heparin solution, 10 mg. per cent in 5 per cent glucose solution. The heparin solution should be injected into the artery as the figure-of-eight stitch is tied down over a piece of Gelfoam, to be sure that the tubing has not been occluded.

The clamps and rubber bands are then released from the distal artery and the branches. Bleeding from the arteriotomy incision generally takes place but the pressure is low and the larger holes can be closed with figure-of-eight stitches of 00000 Deknatel braided silk. As soon as possible, the clamp on the proximal artery should be gradually released to provide for a rapid flow of blood through the previously occluded segment.

The laying of Gelfoam soaked with fibrin along the suture line may afford additional protection, but it should be applied only after all significant bleeding has ceased.

The polyethylene tubing is brought out to the surface of the body, not through the wound, but by passing it through a 16 gauge needle, three inches or more in length, inserted through some convenient place in the skin below the groin, and the injection of heparin is continued.

Before closure of the operative wound, which is made in three layers plus through-and-through stainless steel wire, it is advisable to be sure that hemostasis is complete so that the restored artery cannot be compressed by the formation of a hematoma. We have not used drainage in any of our cases. Bacitracin, 20,000 units of 20 c.c. of solution, has been instilled retroperitoneally in the more recent cases.

After the dressings have been applied and the patient returned to his bed, the continuous intra-arterial injection of heparin solution is maintained. Simple gravity is adequate, provided the height is sufficient to overcome the head of arterial pressure. The speed of injection is altered as necessary, in order to keep the systemic clotting time, as determined by the Lee-White method, close to twenty minutes. This degree of systemic anticoagulant therapy is generally not hazardous.

In the present series, intra-arterial heparinization was successfully carried out in eighteen patients for periods ranging from one to eight days. It was not used in two patients. One of them (Case 6) developed recurrence of thrombosis at the operative site, and in the other (Case 12) small emboli were dislodged to the arteries of the foot. This episode occurred on the ninth postoperative day, three days after anticoagulant therapy was discontinued.

We prefer to continue the intra-arterial heparinization until the prothrombin level has become stabilized in the therapeutic range. We have had no bleeding on removal of the intra-arterial tube. Generalized anticoagulant therapy (Dicumarol or phenidione) was continued during the period of hospitalization (one to two weeks) and discontinued by tapering of the doses just before the date of discharge.

RESULTS

An excellent clinical result was obtained in eighteen patients. They have all recovered their ability to walk without claudication. Thirteen of the fourteen men have noted a return of their ability to maintain an erection although they have been unable to ejaculate. This fact may be explained by the presacral neurectomy necessarily performed in the course of the dissection of the terminal aorta.

Peripheral pulses returned in all but two patients. In Case 8 the left femoral pulse was absent shortly after discharge and has not returned. In spite of this fact the patient has been able to walk without claudication and has no signs of ischemia, probably because of the excellent collateral circulation established previously across the pelvis and about the hips. In Case 18, the patient had previously sustained an occlusion of the right femoral artery. Relief of claudication was noted after operation even though the pedal pulses did not return.

One death occurred from hemorrhage, presumably due to overdosage of heparin (Case 4).

In Case 6 thrombosis recurred at the operative site immediately after operation. The fact that regional heparinization was not used in this patient may be significant.

The patient in Case 2 developed ischemic lesions of nerves and muscles of the limb which was considered to be the less involved before operation. The explanation for this complication may be the fact that the aorta was clamped for a prolonged period and the collateral circulation was not well developed on that side. There followed severe ischemic neuritis with foot drop, which took more than one year to clear up in spite of the return of the posterior tibial pulse shortly after the operation. Since we have been starting the endartectomy with the more distal vessels and working proximally, this complication has not occurred.

At operation the inferior mesenteric artery was found to be patent in fifteen patients. In one patient it was ligated. He developed mild intermittent paralytic ileus which lasted for two months. In five patients this artery

was found to be thrombosed at its take-off, with collateral circulation maintained through anastomosis of the middle colic to the left colic artery. The patient in Case 14 had an arteriosclerotic plaque in the origin of the inferior mesenteric, which was removed with a small curette.

DISCUSSION

Thromboendarterectomy has been found to be a rational approach to the problem of arteriosclerotic occlusion of the terminal aorta and common iliac arteries. In this series we are able to demonstrate good anatomic and clinical results without undue hazard to the patients. The symptoms in these patients were due to a localized or segmental manifestation of a generalized disease, and removal of this segmental block has restored their peripheral arterial circulation. How long this restoration will persist, we are as yet unable to say. It is our impression that the segment of the vessel freed of diseased lining has a better prospect of remaining open than the distal or proximal portions. As to how soon these patients will develop thrombosis in the more distal vessels, we do not know. Only a prolonged follow-up of these patients will give us an answer to this question.

Aneurysm formation has not occurred in our series and, in the literature, only one case has been reported,[20] that of a false aneurysm due probably to a defect in the suture line.

Will these patients succumb to complications of arteriosclerosis in other organs? Our series is too small and the follow-up too short to give an adequate answer to this question. The cerebral thrombosis which developed in Case 1 was the only complication of arteriosclerosis encountered so far in the nineteen patients who have been followed over a period of one to thirty-nine months.

The patients in whom lumbar sympathectomy was performed at the same operation (Cases 2, 9, 11, 15, 19) did not seem to show any differences so far as clinical result was concerned. We think that sympathectomy should be considered if the patient shows clinical evidence of increased vasomotor tone, since it is possible that these patients will develop further obliterative disease in the distal arteries.

SUMMARY

Twenty patients with arteriosclerotic occlusion of the terminal aorta or common iliac arteries were submitted to thromboendarterectomy. There was one death. One patient developed postoperative thrombosis at the site of operation. Nineteen have been followed for from one to thirty-nine months, and with one exception have fully recovered from the impairment of circulation to the lower extremities and pelvis.

CONCLUSIONS

Thromboendarterectomy is of benefit to patients with circulatory impairment due to occlusion or stenosis of the aorta and common iliac arteries. The low morbidity and mortality make this operation useful in selected cases.

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A CRITICAL EVALUATION OF LUMBAR SYMPATHECTOMY FOR PERIPHERAL ARTERIOSCLEROTIC VASCULAR DISEASE

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IT HAS become apparent, from numerous reports during the past eight years,[1-10] that lumbar sympathectomy for peripheral arteriosclerotic vascular disease has definite benefit in certain patients. As might be anticipated, however, such benefits do not universally occur in all patients undergoing this procedure. This report deals with the results of 397 lumbar sympathectomies performed in 275 patients at the University of Michigan Hospital during the period of 1945-1952 for arteriosclerosis obliterans of the lower extremities. In addition to standard evaluation of results, particular emphasis has been placed upon longevity following operation, critical analysis of reasons for success or failure, and criteria that possibly could be used preoperatively to estimate potential benefit. A follow-up was obtained in 271 patients (98 per cent) (Table I).

AGE

The majority of patients (72 per cent were between 50 and 70 years of age with the highest incidence in the seventh decade (Table II, Fig. 1). Twenty patients under 45 years of age were included. All of them had either confirmatory evidence of degenerative vascular disease by direct pathologic examination or demonstrated calcification of peripheral vessels on x-ray examination. Eleven patients were over 75 years of age. Sex distribution in regard to age was essentially the same.

SEX AND RACE

Of the 275 patients, 216 were white male (79 per cent), 53 white female (19 per cent), 4 Negro male (1.5 per cent) and 2 Negro female (0.5 per cent). (Table II, Fig. 1.) For every Negro patient registering at this hospital there are 19 white. In this study, the ratio of white to Negro was 45:1, the incidence in whites being more than twice that of Negroes. It is of interest to note that in a previously reported series from a large Southern clinic, the incidence of arteriosclerosis obliterans tended to parallel the race ratio of total registrations.[7] Essentially this is a disease of males when consideration of diabetes is excluded.

CLASSIFICATION

It is difficult to offer clear-cut group classifications because of such variables as duration of symptoms, extensiveness of vascular involvement, sub-

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jective interpretation of pain intensity, and the significance of tissue necrosis. Gangrene, for example, may have a better prognosis in an individual with a symptomatic history of considerable duration than in one with a short history associated with widespread peripheral vascular involvement. The following classification is therefore used as an implement to analysis of data. Certain subgroups have been worked out under each heading in an attempt to clarify results and prognostic import, they have been included in each group rather than creating a cumbersome primary classification (Table III).

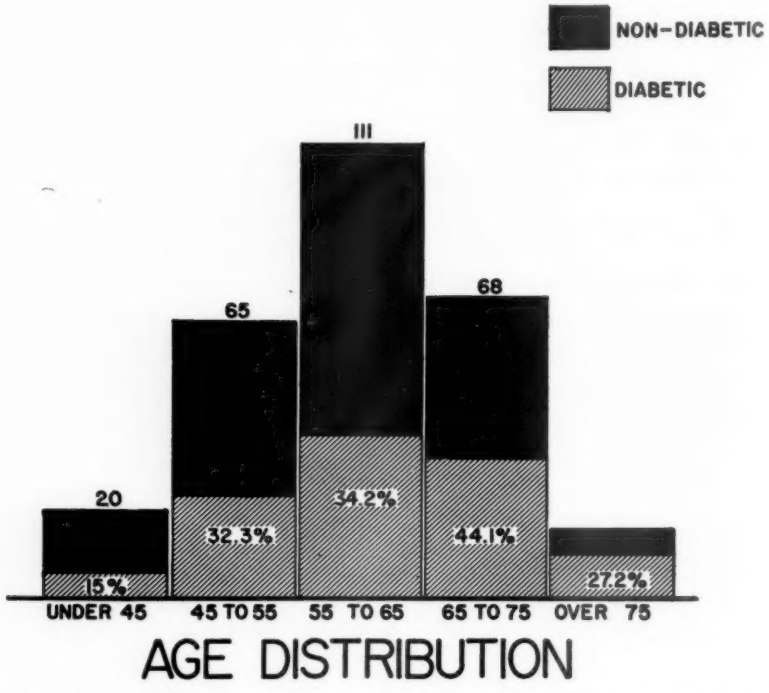

Fig. 1.—Age distribution and incidence of diabetes in 275 sympathectomized patients.

Group 1. Intermittent claudication only.

Group 2. Mild rest pain with or without intermittent claudication. Pain may need little if any medication and is controlled by mild analgesics and sedatives.

Group 3. Severe constant pain with or without intermittent claudication. Control of pain in this group usually requires the use of narcotics.

Group 4. Tissue necrosis with or without intermittent claudication and/or pain.

Group 5. Asymptomatic. Lumbar sympathectomies performed prophylactically in patients with one amputation to implement circulation in the contralateral limb.

A minimum twelve-month follow-up was obtained in 271 patients. If complete alleviation or significant improvement followed operation, the result has been classified as good. The result has been designated as poor if minimal or no improvement was obtained and amputation was not necessary. Am-

putations, also representing poor results, have been separately grouped. All amputations recorded here are either supracondylar (by far the majority) or just below the knee joint. Tabulation of those who have died since leaving the hospital includes all dead regardless of the result of operation.

TABLE I. LUMBAR SYMPATHECTOMY FOR ARTERIOSCLEROTIC PERIPHERAL VASCULAR DISEASE 1945-1952

Patients	275
Operations	397
Follow-up	271 (98%)

TABLE II. AGE AND RACE DISTRIBUTION OF 275 LUMBAR SYMPATHECTOMY PATIENTS

AGE	NO.
Under 40	5
40-45	15
45-50	22
50-55	43
55-60	43
60-65	68
65-70	45
70-75	23
Over 75	11

	White	*Negro*
Male	216 (79%)	4 (1.5%)
Female	53 (19%)	2 (0.5%)

TABLE III. CLASSIFICATION OF PATIENTS UNDERGOING LUMBAR SYMPATHECTOMY

	NUMBER OF PATIENTS
Group 1. Intermittent claudication only	41
Group 2. Rest pain—intermittent mild or moderate	24
Group 3. Rest pain—severe constant	43
Group 4. Tissue necrosis	165
Group 5. Asymptomatic	2

All sympathectomies were performed through transverse incisions immediately lateral to the umbilicus with extraperitoneal dissection. The sympathetic chain was removed between the second lumbar vertebra and the bifurcation of the aorta. Removal of the sympathetic chain was confirmed by histologic examination in all operations except two.

RESULTS

Group 1. Intermittent Claudication Only, 41 Patients.—Based upon severity, three subgroups have been designated in an attempt to further correlate results. It is fully realized that the symptom of intermittent claudication, because of its subjective nature, is difficult to interpret objectively.

	Number of Patients
Mild claudication—walking distance limited but not less than three to four blocks.	11
Moderate claudication—walking distance limited to one to two blocks.	25
Severe claudication—walking distance limited to less than 100 feet.	5

Thirty patients are living, the average time since operation being about forty-eight months (Table IV). Four are six to eight years postoperative. Including two hospital deaths, 11 patients have died.

TABLE IV. GROUP 1, 41 PATIENTS. INTERMITTENT CLAUDICATION ONLY. RESULTS BASED UPON SURVIVAL AND DEGREE OF CLAUDICATION

DEGREE OF CLAUDICATION	GOOD RESULT	POOR RESULT, NO AMPUTATION	AMPUTATIONS	HOSPITAL DEATHS
		Patients Living (30)		
Mild	5	1	2	0
Moderate	10	9	0	0
Severe	1	2	0	0
		Patients Dead (11)		
Mild	1	1	1	0
Moderate	3	2	0	1
Severe	0	0	1	1
Total	20 (49%)	15 (39%)	4 (10%)	2

Twenty patients (49 per cent) obtained a good result (Table IV), 16 obtained no benefit but have not had amputation, amputation has been necessary in 4, and 9 have died since leaving the hospital.

There would appear to be some correlation between severity of claudication and result. Good results were obtained in 6 of 10 patients with mild claudication, 13 of 25 with moderate claudication, and only 1 of 5 with severe claudication. The number of cases is too small to be of statistical significance.

Of four amputations, 2 patients obtained significant benefit following sympathectomy only to be followed in one to two years by deterioration and amputation. One amputation was performed ten days following sympathectomy because of the rapid onset of gangrene. Subsequent autopsy revealed erosive abdominal aortitis with thrombosis and multiple emboli. In this case "paradoxical gangrene" was caused by arterial embolization of the involved leg.

Thirty-one patients in this group also complained of "cold feet." Four observed increased warmth of the extremity without improvement of claudication. These results have been classified as poor. The incidence of cold feet is of no prognostic significance when correlated with end results.

Group 2. Mild Ischemic Pain With or Without Claudication, 24 Patients.—Ischemic pain, like claudication, is difficult to interpret objectively. The degree of pain has been designated as "mild" because of apparent minimal demand for relief and satisfactory control with mild analgesics and sedatives.

Intermittent claudication was an accompanying symptom in all but 3 patients (Table V), the degree being mild in 7, moderate in 9, and severe in 5. The severity of claudication, however, could not be significantly correlated with end result.

Sixteen patients are alive. The average time since operation in those who are living and obtained a good result is fifty-one months.

Ten patients (42 per cent) obtained a good result. This includes 2 patients who obtained excellent relief of pain but observed little increase in walking distance. Seven (29 per cent) obtained no benefit and amputations have been performed on 7, none obtaining any help prior to amputation.

TABLE V. GROUP 2, 24 PATIENTS. MILD PAIN WITH OR WITHOUT CLAUDICATION. RESULTS BASED UPON SURVIVAL AND DEGREE OF CLAUDICATION

DEGREE OF CLAUDICATION	GOOD RESULT	POOR RESULT, NO AMPUTATION	AMPUTATION
	Patients Living (16)		
Mild	2	1	3
Moderate	2	1	0
Severe	3	0	1
None	2	1	0
	Patients Dead (8)		
Mild	1	0	0
Moderate	0	3	3
Severe	0	1	0
None	0	0	0
Total	10 (42%)	7 (29%)	7 (29%)

Group 3. Severe Pain With or Without Claudication, 43 Patients.—The degree of pain has been designated "severe" if it was constant, incapacitating, and required narcotics and large doses of sedatives for relief.

Thirty-three patients had intermittent claudication graded as follows: mild, 7; moderate, 21; and severe, 5. The end results in patients with no or mild claudication were somewhat better than those with moderate or severe type (Table VI).

TABLE VI. GROUP 3. SEVERE PAIN WITH OR WITHOUT INTERMITTENT CLAUDICATION, 43 PATIENTS. CORRELATION OF RESULTS WITH SURVIVAL AND DEGREE OF CLAUDICATION

DEGREE OF CLAUDICATION	GOOD RESULT	POOR RESULT, NO AMPUTATION	AMPUTATIONS	HOSPITAL DEATHS	NO FOLLOW-UP
		Living (20)			
Mild	4	0	0	-	0
Moderate	5	1	3	-	0
Severe	2	0	1	-	0
None	3	0	0	-	1
		Dead (23)			
Mild	0	3	0	0	-
Moderate	1	5	5*	2	-
Severe	0	1	0	1	-
None	2	2	2	0	-
Total	17 (40%)	12 (28%)	11 (25%)	3	1

*One bilateral amputation.

Seventeen (40 per cent) obtained a good result, a surprisingly large number when the severity of the pain is considered. Only 3 of these patients have died. Twelve (28 per cent) had little benefit from operation but did not require amputation. Eleven of this subgroup have died usually within one year after sympathectomy. Eleven amputations were necessary in forty-four sympathectomized extremities (25 per cent); 3 patients died in the hospital following operation and 1 was lost to follow-up. Including hospital deaths, 23 patients are dead. This is the lowest survival rate of the four major groups.

Group 4. Tissue Necrosis With or Without Claudication and/or Pain, 165 Patients.—Ulceration, gangrene, or both were present in 165 patients (60 per cent of this study). No attempt has been made to distinguish between ulceration or gangrene because there was no statistically significant difference ob-

served in the end result, and therefore they have been included together as tissue necrosis. In general, however, patients with gangrene had a slightly higher percentage of good results than those with ulceration. Poorest results were observed when both ulceration and gangrene were present.

Results have been classified as for the previous three groups. A good result also designates that sympathectomy apparently importantly contributed to the healing of tissue necrosis, in addition to significant alleviation of concomitant symptoms.

For purposes of analysis this group has been divided into the following subdivisions:

	Number of Patients
1. Necrosis and pain.	59
2. Necrosis, pain, and claudication.	51
3. Necrosis alone.	35
4. Necrosis and claudication.	20

Results in its four subdivisions and summary of Group 4 are presented in Table VII. Numbers in parentheses represent dead patients. The summary reveals that 47 (28 per cent) obtained a good result, 21 (13 per cent) a poor result without amputation, ninety-seven amputations were performed in 86 patients (amputation rate 55 per cent), and 69 (42 per cent) have died. Eight of 47 patients obtaining a good result have died, as have 16 of 21 with a poor result. Forty of the 86 patients on whom amputation was performed are also dead.

TABLE VII. GROUP 4. TISSUE NECROSIS, 165 PATIENTS. BREAKDOWN BASED UPON ACCOMPANYING PAIN AND CLAUDICATION

	NUMBER OF PATIENTS	GOOD RESULT	POOR RESULT, NO AMPUTATION	AMPUTATIONS	DEAD	HOSPITAL DEATH	NO FOLLOW-UP
Necrosis and pain	59	14 (4)* 26%	5 (4) 8%	44 (19) 69% 39 patients	27 (46%)	1	-
Necrosis, pain, and claudication	51	13 (1) 26%	6 (5) 12%	32 (14) 59% 29 patients	22 (43%)	-	1
Necrosis only	35	14 (2) 40%	6 (4) 17%	11 (5) 31% 10 patients	13 (37%)	2	1
Necrosis and claudication	20	6 (1) 30%	4 (3) 20%	10 (2) 45% 8 patients	7 (35%)	-	1
Total	165	47 (8) 28%	21 (16) 13%	97 (40) 55% 86 patients	69 (42%)	3	3

*Numbers in parentheses represent patients who have died.

The best results in Group 4 were observed in patients who presented tissue necrosis without pain or intermittent claudication. Of these 35 patients, 25 (70 per cent) were diabetic. The highest percentage of good results (40 per cent) and the lowest amputation rate (31 per cent) were observed in this group. Poorest results attended the 59 patients presenting themselves with necrosis and severe pain. Sixty-nine per cent in this group eventually

had amputation and 46 per cent of all patients are dead. The results in 51 patients presenting necrosis, pain, and claudication are only slightly better, as the amputation rate was 59 per cent and 43 per cent are now dead.

Group 5.—Two patients have been arbitrarily placed in this group because they were asymptomatic at the time of sympathectomy. Both had a previous supracondylar amputation and, although asymptomatic, had absent peripheral pulses in the remaining leg. The operation was prophylactic in an attempt to improve the circulation of the remaining leg. Potential long-term beneficial effects could not be observed, however, as both patients died within two years.

Summary of Results in 275 Patients.—The end results for all patients and comparative results between Group 4 and the combined results of Groups 1, 2, 3, and 5 are shown in Table VIII. Good results were obtained in 94 patients (34 per cent), 16 of whom are dead. Poor results without amputation were observed in 55 (20 per cent), 34 of whom have died. One hundred nineteen amputations were performed in 107 patients (amputation rate 41 per cent), bilateral amputation being necessary in 12. Fifty-one amputees are dead. Of all patients operated on, 108 (39 per cent) are now dead.

TABLE VIII. RESULTS IN 275 PATIENTS AND COMPARATIVE RESULTS BETWEEN GROUPS 1, 2, 3, AND 5 AND GROUP 4

		GOOD RESULTS	POOR RESULTS, NO AMPUTATION	AMPUTATIONS	DEAD	HOSPITAL DEATHS	NO FOLLOW-UP
Groups 1, 2, 3, and 5	(110)	47 (8) 43%	34 (18) 31%	22 (11) 20%	39 (35%)	5	1
Group 4	(165)	47 (8) 28%	21 (16) 13%	97 (40) 55%	69 (42%)	3	3
Total	(275)	94 (16) 34%	55 (34) 20%	119 (51) 41%	108 (*39%)	8	4

*This includes 5 patients who died soon after leaving the hospital. Adequate evaluation was not possible.

Comparison of patients with and without tissue necrosis reveals that there is a significantly higher percentage of good results if ulceration or gangrene has not developed. There is also a considerably higher percentage of poor results without amputation in patients who do not have tissue necrosis. The amputation rate in patients with ulceration or gangrene is more than two and one-half times that of those without. The percentage of dead patients is slightly higher in those with tissue necrosis.

DIABETES

It has been estimated that there are one and one-half million known diabetic persons in the United States and again as many who have the disease and are unaware of it. The presence of diabetes was confirmed in 93 (34 per cent) of the patients in this study. It is obvious, therefore, that diabetes contributes importantly to the development of degenerative peripheral vascular disease.

Of the 216 white males, 50 (23 per cent) were diabetic. There was a significantly greater percentage of white females with diabetes, as 41 of 53 (77

per cent) were so afflicted. Both Negro females were diabetic (Figs. 1 and 2). Eighty-two per cent of all diabetic persons were in Group 4.

Age distribution followed that of the whole study group. Table IX presents a comparative analysis of the results in diabetic and nondiabetic patients. Further breakdown has been accomplished by comparing Group 4 with the combined results of the other groups. The percentage of good results tends to be parallel in all groups with the exception of the nondiabetic patients of Group 4 (27 per cent) as compared to the combined results of nondiabetic persons in the other groups (44 per cent). Amputation rate for sympathectomized limbs in diabetic patients was 50 per cent as compared to 37 per cent for nondiabetic patients. The percentage dead is somewhat higher in diabetic patients than in the nondiabetic patients.

The results of diabetic and nondiabetic patients in Group 4 have been compared in Table X. The results have remarkable parallelism.

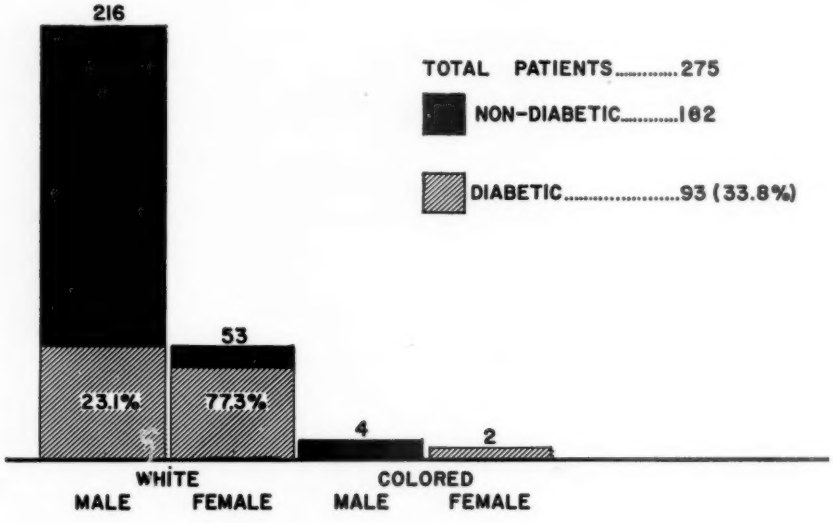

Fig. 2.—Race, sex, and incidence of diabetes.

Further comparative results in diabetic patients are shown in Table XI, the results being tabulated according to severity of disease, duration, and adequacy of treatment. Diabetes was classed as mild (62 patients) if dietary control was adequate or less than 15 units of insulin daily was needed, moderate (26 patients) if 15 to 40 units of insulin was necessary daily, and severe (5 patients) if more than 40 units was needed for control. Duration was considered long if the disease had been present more than five years (54 patients), short (23 patients) if less than five years, and the disease was discovered in fifteen patients during hospitalization for symptomatic peripheral vascular disease. Adequacy of treatment was determined by history and diabetic work-up in the hospital. Good results were essentially the same in all groups regardless of severity, duration, or adequacy of treatment. It was of interest to observe that the highest amputation rate was observed in patients who had a short history of diabetes or whose disease was initially un-

covered during hospitalization. The results in adequately treated diabetic persons were somewhat better than in the inadequately treated group although the inadequately treated diabetic patient had as good a chance for survival as did the adequately treated patient. This could conceivably be related to the consideration that diabetic patients discovered in the hospital were classed as inadequately treated.

TABLE IX. COMPARATIVE ANALYSIS OF RESULTS IN NONDIABETIC AND DIABETIC PATIENTS

	GOOD RESULTS	POOR RESULTS, NO AMPUTATION	AMPUTATIONS	DEAD	HOSPITAL DEATH	NO FOLLOW-UP
Nondiabetic Patients						
Groups 1, 2, 3, and 5	(93) 41 (7) 44%	29 (15) 31%	17 (8) 18%	31 33%	5	1
Group 4	(89) 24 (4) 27%	11 (9) 12%	54 (21) 56%	37 42%	1	3
Total nondiabetic patients	(182) 65 (11) 36%	40 (24) 22%	71 (29) 37%	68 37%	6	4
Diabetic Patients						
Groups 1, 2, 3, and 5	(17) 6 (1) 35%	5 (3) 30%	5 (3) 30%	8 47%	-	-
Group 4	(76) 23 (4) 30%	10 (7) 13%	43 (19) 54%	32 42%	2	-
Total diabetic patients	(93) 29 (5) 31%	15 (10) 16%	48 (22) 50%	40 43%	2	-

TABLE X. COMPARATIVE ANALYSIS OF RESULTS IN NONDIABETIC AND DIABETIC PATIENTS IN GROUP 4

	GOOD RESULT	POOR RESULT, NO AMPUTATION	AMPUTATIONS	DEAD	HOSPITAL DEATH	FOLLOW-UP
Nondiabetic Patients (89)						
Necrosis (10)	5 (1)	0	3 (1)	3	1	1
Necrosis and pain (25)	5 (1)	4 (3)	17 (9)	13	0	0
Necrosis and claudication (14)	4 (1)	2 (2)	8 (2)	6	0	1
Necrosis, pain, and claudication (40)	10 (1)	5 (4)	26 (9)	15	0	1
Diabetic Patients (76)						
Necrosis (25)	9 (1)	6 (4)	8 (4)	10	1	0
Necrosis and pain (34)	9 (3)	1 (1)	27 (10)	14	1	0
Necrosis and claudication (6)	2	2 (1)	2	1	0	0
Necrosis, pain, and claudication (11)	3	1 (1)	6 (5)	7	0	0
Nondiabetic patients	24 (4) 27%	11 (9) 12%	54 (21) 56%	37 42%	1	3
Diabetic patients	23 (4) 30%	10 (7) 13%	43 (19) 54%	32 42%	2	0
	47 (8) 28%	21 (16)	97 (40)	69	3	3

Younger diabetic patients obtained a better result than their elders. Eleven of 23 patients with diabetes and under 55 years of age obtained a good result.

AMPUTATIONS

One hundred nineteen sympathectomized extremities in 107 patients have undergone a major amputation, an amputation rate of 41 per cent (Table

XII). Of the 12 patients who have lost both legs following bilateral sympathectomy, only 3 are alive. Two, both diabetic, have lived four years, and one, who is nondiabetic, is alive after eighteen months. Seven patients with unilateral sympathectomy have lost both legs. Three, 1 diabetic, are still living thirty-six to forty-eight months following sympathectomy.

TABLE XI. COMPARATIVE RESULTS IN 93 DIABETIC PATIENTS IN REGARD TO SEVERITY OF DIABETES, ESTIMATED DURATION, AND ADEQUACY OF TREATMENT

		GOOD RESULT	AMPUTATIONS	DEAD
Severity of diabetes				
Mild	(62)	17 (28%)	24 (36%)	26 (42%)
Moderate	(26)	8 (31%)	13 (47%)	12 (46%)
Severe	(5)	3 -	1 -	2 -
Duration				
Long	(54)	18 (33%)	23 (42%)	21 (39%)
Short	(23)	7 (30%)	14 (58%)	14 (61%)
Discovered in hospital	(15)	4 (26%)	11 (69%)	5 (30%)
Adequacy of treatment				
Adequate	(65)	21 (32%)	31 (45%)	29 (45%)
Inadequate	(28)	7 (25%)	17 (61%)	11 (39%)

TABLE XII. AMPUTATIONS PERFORMED PRIOR TO AND FOLLOWING LUMBAR SYMPATHECTOMY. OF THE 19 BILATERAL AMPUTATION PATIENTS, 12 HAD BILATERAL SYMPATHECTOMY

Total amputations including major amputations prior to sympathectomy	162
Major amputations prior to sympathectomy	36
Amputations following hospitalization for sympathectomy	126
Bilateral amputation following unilateral sympathectomy	7
Sympathectomized limbs amputated	119
Bilateral amputations following bilateral sympathectomy	12
Sympathectomized patients undergoing amputation	107

Twenty-two amputations were necessary in the 110 patients of Groups 1, 2, and 3. The interval between sympathectomy and amputation for the four patients in Group 1 who had amputation was twelve to twenty-four months and for seven amputations in Group 2 averaged only three months. Two living amputees in Group 3 obtained a good initial result, but rapid deterioration after twelve to twenty-four months necessitated amputation. The remainder had an amputation interval of but two and one-half months.

The remaining ninety-seven amputations were performed on Group 4 patients. The average amputation interval for nondiabetic persons was 5 months and for diabetic persons 3.6 months. Fifty per cent, however, lost their legs in less than 3 months.

Arrest of necrosis or significant alleviation of symptoms was obtained by 17 patients, only to be followed by deterioration in less than two years with resultant amputation. These patients have been classed in the amputation group only.

Thirty-six patients, 17 of whom were diabetic, had a previous major amputation before undergoing lumbar sympathectomy. The end results in these patients are shown in Table XII. Of the 12 obtaining a good result, 7 were diabetic. No benefit was obtained in 5 and amputation was necessary

in 16 patients, the amputation interval being one to three months. Seven of these bilateral amputees are living. Eighteen patients (50 per cent) are dead, the average survival time being less than one year.

Of 21 patients presenting themselves with minor amputations (one or more toes) prior to sympathectomy, 14 came to major amputation. Five obtained a good result and 2 died shortly after leaving the hospital.

Only two transmetatarsal amputations were performed following sympathectomy. Although the amputations were successful, the operation from the patient's point of view was a failure.

OPERATION MORTALITY AND SUBSEQUENT LONGEVITY

Eight patients died in the hospital following sympathectomy. Four deaths were due to coronary thrombosis, three to thrombosis of the aorta with retrograde obturation and renal failure, and one to erosive abdominal aortitis with thrombosis and multiple emboli. Autopsy was carried out in all cases.

Life expectancy of the general population from 40 to 75 years of age obtained from mortality tables of the Prudential Life Insurance Company is shown in Table XIII.[11] Average survival periods of the 108 sympathectomized patients who have died are tabulated according to groups in Table XIV. The 69 dead in Group 4 have lived an average of twenty-six months and the 37 in Groups 1, 2, 3, and 5, twenty-three months. The average time for all groups is twenty-five months. One-third, however, died in less than one year.

TABLE XIII. LIFE EXPECTANCY ACCORDING TO AGE IN THE GENERAL POPULATION OF THE UNITED STATES

AGE (YR.)	LIFE EXPECTANCY (YR.)
35-40	30.8
40-45	26
45-50	22
50-55	19
55-60	16
60-65	13
65-70	9.5
70-75	8
75-80	6.44

TABLE XIV. SURVIVAL PERIODS OF DEAD PATIENTS ACCORDING TO GROUPS

	NUMBER DEAD	SURVIVAL PERIOD (MO.)
Group 1	9	32
Group 2	8	13
Group 3	20	23
Group 4	69	26
Group 5	2	24
Average		25

Patients living with a good result have survived an average of forty-nine months in Group 1, fifty-one months in Group 2, and forty months in Group 3. Survivors with good results in Group 4 are equally divided between diabetic and nondiabetic persons. Those with diabetes have lived an average of forty-six months and the nondiabetic patients forty-three months.

Information regarding the cause of death has been considered reliable in 82 patients. Seventy-four have died of causes related to generalized arteriosclerotic vascular disease. Eight have died of other causes.

COMMENT

In a previous report from this clinic,[5] follow-up studies covering a two and one-half year period revealed that about 70 per cent of patients undergoing lumbar sympathectomy for arteriosclerosis obliterans obtained some measure of alleviation of symptoms. The present study has permitted the results over an eight-year period to be reported. Increased experience has necessitated a more critical approach in order to establish whether or not a good result has been obtained. If the patient has felt that significant alleviation of symptoms has been obtained and he was reasonably satisfied, the result has been called good. Any other result, from the patient's point of view, has essentially been a failure. Ninety-four (34 per cent) have obtained a good result, with the highest percentage in those with intermittent claudication as the only symptom. Certain of these patients have been followed from three to seven years and continue to maintain their improvement and lead useful lives.

Two points are of interest in the 55 patients who were classified as a poor result without amputation. Of the 40 in Groups 1, 2, and 3, 31 have died, the majority of them within one year. It could be reasoned that although no subjective benefit was obtained, sympathectomy permitted the patient to live with his disease and importantly contribute to arrest of peripheral ischemia. The high death rate in this group, however, would suggest that this is not the case and that the poor result was related to a more severe type of generalized arteriosclerotic disease. As a paradox are the 15 patients in Group 1 who observed no increase in walking distance following sympathectomy. Only 3 are dead. It would therefore seem quite possible that severe arteriosclerotic segmental involvement of vessels of the posterior calf muscles could occur without rest pain, tissue necrosis, or severe generalized disease.

Comparison of life expectancy of the general population with the short survival periods of over one-third of patients in this study (Tables XIII and XIV) emphasizes the well-accepted consideration that arteriosclerotic obliterans is but one manifestation of generalized arteriosclerotic disease.

Factors Related to Preoperative Evaluation of Potential Results From Sympathectomy.—It would be of great value if criteria could be established to predict accurately which patient would obtain a good result from lumbar sympathectomy. After careful evaluation of the results in this study no single consideration absolutely contraindicated sympathectomy in Groups 1, 2, and 3 provided that the patient's general condition did not make the operative risk prohibitive. In regard to Group 4 patients, a common sense approach will prevent many useless sympathectomies. It is obvious that extensive necrosis of the foot and/or the lower third of the leg resulting from advanced arteriosclerosis obliterans will be little benefited by such operation.

Factors that may be of importance in preoperative estimation of results include age of the patient, duration of symptoms, severity of pain, severity and

location of foot necrosis, tissue atrophy and capillary anoxia, degree of arterial involvement as manifested by palpation of peripheral pulses, concommitant diabetes, arteriosclerotic involvement of other organs, and the response to lumbar block. It must be pointed out that none of these interpreted independently has any absolute significant prognostic import.

As a group, patients over 65 years of age do not achieve a good result, while the percentage of patients under 50 years of age obtaining significant benefit is higher than the group average. Excellent results in patients over 70 years of age have been observed, however, and certain patients in this study under 50 years of age not only have had amputation shortly after sympathectomy, but have died soon thereafter. Duration of symptoms has little significance in Groups 1, 2, and 3. In Group 4 patients, however, a symptomatic history of one to six months prior to operation was often followed by amputation or death in a short period of time. Certain patients with an extremely short history obtained beneficial results, however. Atrophy of the soft part of the leg with attendant severe capillary anoxia (marked pallor upon elevation, rubor on dependency, sluggish capillary pulse and edema) is particularly serious, and results in this group are almost universally bad. Yet there are two cases in this study with such attendant clinical picture and good results. The significance of absent peripheral pulses below the femoral arteries depends upon careful correlation with other symptoms and physical findings. A minimum of absent pulses is often, but not always, followed by a good result. Obvious widespread vascular involvement, however, certainly does not contraindicate sympathectomy. Severe pain involving only the toes has a better prognosis than pain involving the foot or the lower third of the leg. If the popliteal pulses are palpable, the chance of obtaining a favorable result with ischemic foot pain is increased. The beneficial effects in nondiabetic persons are somewhat better than in diabetic patients. Under 55 years of age, good results may be anticipated in 50 per cent of diabetic patients. Over 65 years of age, results in diabetic patients are, with rare exception, poor, particularly if arteriosclerotic involvement of other organs is present.

Arteriosclerotic involvement of the heart, brain, and significant elevation in systolic blood pressure, but not to a degree to contraindicate operation, were present in 152 patients in this group. Thirty per cent of such patients in Groups 1, 2, and 3 are living, having obtained a good result. In Group 4 only 20 per cent were included as alive with benefit. Such arteriosclerotic involvement by itself does not necessarily contraindicate operation.

Lumbar block, as an element of prognosis, is of little value in the majority of cases because the absence of response to block cannot be correlated with result. A significant rise in peripheral temperatures or relief of pain following block was demonstrated by a limited few patients. Good results generally followed such response. A lowering of peripheral temperatures following lumbar block, the so-called "paradoxical response," is indeed a rare phenomenon in this study and requires careful evaluation. Diagnostic spinal anesthesia should be used to confirm such response to be sure that it does not

represent reflex vasoconstriction secondary to psychic stress of lumbar block rather than the potential opening of arteriovenous shunts and diminished effective pressure produced by decreasing peripheral resistance.

From the results of this study the following types of patients are offered as having a minimum chance of obtaining a good result from lumbar sympathectomy. None, however, represent absolute contraindications to operation:

1. Elderly diabetic persons (over 65 years of age) with clinical evidence of arteriosclerotic involvement of other organs or elevated systolic blood pressure.
2. Severe atrophy of the soft parts of the leg with evidence of marked capillary anoxia.
3. Severe pain involving the foot or lower third of the leg with absent popliteal pulses.
4. A rapidly progressing process with widespread arterial involvement.
5. Gangrene or ulceration involving the foot in patients over 60 years of age with severe pain and obliteration of the popliteal pulses.

Bilateral Versus Unilateral Operation.—Of the 397 sympathectomies, 165 were unilateral and 116 bilateral. Good results were observed following unilateral sympathectomy in 49 patients (31 per cent) and in 45 (37 per cent) following bilateral operation. The amputation rate was approximately the same. Although the difference in results is not striking, evidence is weighted in favor of bilateral operation by the following: (1) during the first four years bilateral operation was not routine, but was performed in bilateral disease and severe unilateral disease, these essentially being the worst cases; and (2) certain patients with unilateral operation had the onset of symptoms in the previously asymptomatic unsympathectomized leg within a short period of leaving the hospital. Although this could represent a progression of disease, a more probable explanation is that the added stress on the unsympathectomized limb precipitated relative symptomatic peripheral ischemia.

SUMMARY

1. A critical review of the results of 391 lumbar sympathectomies in 275 patients during the years 1945-1952, inclusive, has been presented.

2. Good results were obtained in 94 (34 per cent) and poor results without amputation in 55 (20 per cent). One hundred seven major amputations were performed on 119 patients, and 108 patients are dead, the average survival time being twenty-five months. One-third lived less than one year.

3. Comparative analysis of diabetic and nondiabetic patients with ulceration or gangrene reveals the results to be essentially the same.

4. Factors affecting anticipated results from sympathectomy have been discussed and, based upon the results of this study, five categories have been presented in which the minimal number of good results were obtained.

5. Evidence is presented supporting the desirability of bilateral operation provided that it is compatible with the patient's general condition.

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APPLICATION OF THE PHYSIOLOGIC PRINCIPLE OF HEMOMETAKINESIA TO THE TECHNIQUE OF LUMBAR SYMPATHECTOMY

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DURING the past fifteen years I have investigated intensively the surgical anatomy of the sympathetic vasomotor innervation of the lower extremity as it applies to the technique of and the peripheral circulatory response to "low" lumbar sympathectomy. For the purposes of this study a standardized technique has been used. The lumbar sympathetic ganglia have been exposed through an anterior, muscle-splitting, retroperitoneal approach. According to the particular clinical situation, the nerve has been severed at certain predetermined levels and a silver clip applied to the cephalic cut end. All accessible lumbar ganglia and their rami caudad to this point would then be excised, taking care to destroy, when present, an inconstant ramus connecting the third lumbar spinal nerve with the caudal portion of the lumbar sympathetic trunk. (See Fig. 1.) This ramus may deliver preganglionic neurons to the caudal lumbar and the sacral ganglia.

The point at which the trunk was severed cephalically has been correlated with postoperative skin temperature and sweating studies, with oscillometric studies, with the general clinical response, and with the position of the silver clip in relation to the lumbar vertebrae as shown by x-ray film. A portion of this study is summarized in Fig. 2. At the bottom of the figure is a diagram of that portion of the lumbar sympathetic nerve which can be visualized through an anterior, muscle-splitting, retroperitoneal approach. *A*, *B*, and *C* mark the points at which the nerve has been severed cephalically according to the clinical indications.

When the large ganglion which is conected with the first lumbar ganglion and the second lumbar spinal nerve cephalically and the third lumbar spinal nerve caudally was bisected at point *A*, the position of the silver clip has been within zone *A* in the upper diagram, and the extent of the sudomotor and vasomotor denervation of the skin of the anterior aspect of the limb is depicted in figure *A*. The latter includes the skin of the lower portion of the thigh, the entire leg, and the foot. Segmentally, this corresponds to the terminal distribution of postganglionic vasomotor and sudomotor sympathetic fibers through the third, fourth, and fifth lumbar spinal nerves and the sacral plexus.

When the lumbar sympathetic trunk has been severed midway between the third and fourth lumbar vessels at point *B*, x-ray films have revealed the

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silver clip to be within zone *B*, and the extent of the cutaneous sudomotor and vasomotor denervation is depicted in figure *B*. Total cutaneous denervation has been obtained consistently in the foot, ankle, and outer leg, while the skin

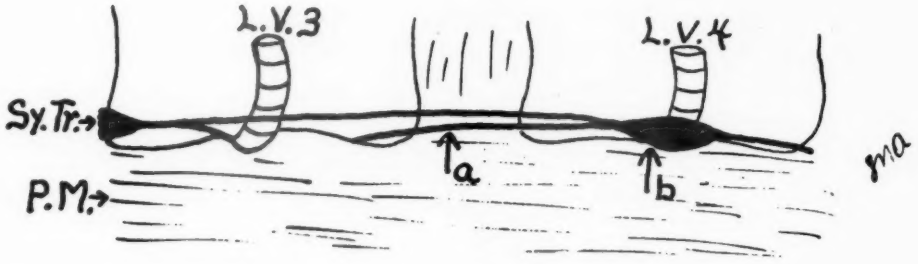

Fig. 1.—*L.V.*, Lumbar veins; *Sy. Tr.*, lumbar sympathetic trunk; *P.M.*, psoas muscle; *b*, sympathetic ganglion; *a*, inconstant accessory (preganglionic?) ramus connecting third lumbar spinal nerve with caudal portion of lumbar sympathetic nerve.

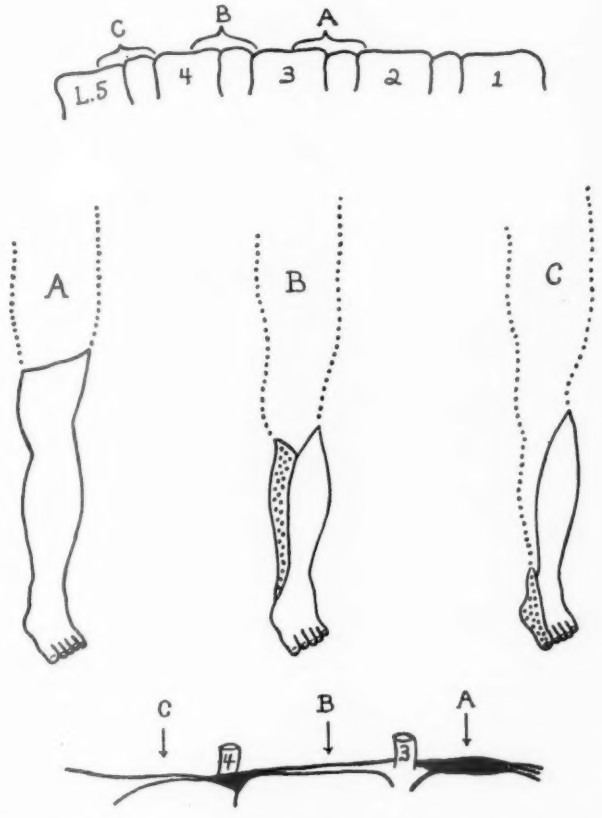

Fig. 2.—Relationship between the point of section of the lumbar sympathetic nerve (lower diagram), the location of the clipped cephalic cut end as revealed by postoperative x-ray film (upper diagram), and the extent of total and partial cutaneous sympathetic denervation of the anterior aspect of the limb (middle diagrams).

at the inner aspect of the leg between the knee and the internal malleolus has been completely to only partially denervated. The sympathetic innervation of this portion of the cutis is via the saphenous branch of the femoral

nerve, and sympathetic fibers distributed through the third lumbar spinal nerve may reach the skin of the inner aspect of the leg in this manner. Segmentally, the total cutaneous denervation corresponds to the terminal distribution of postganglionic fibers through the fourth and fifth lumbar spinal nerves and the sacral plexus. Vasomotor fibers to the intrinsic circulations of the gluteal musculature, the ham strings, and the muscle groups distal to the knee joint are also distributed through these particular nerves. (See Fig. 3.) Thus, a vasomotor denervation sufficiently extensive to meet the clinical requirements of a significant number of peripheral circulatory disturbances can be obtained by sectioning the lumbar sympathetic nerve cephalically at point *B*.

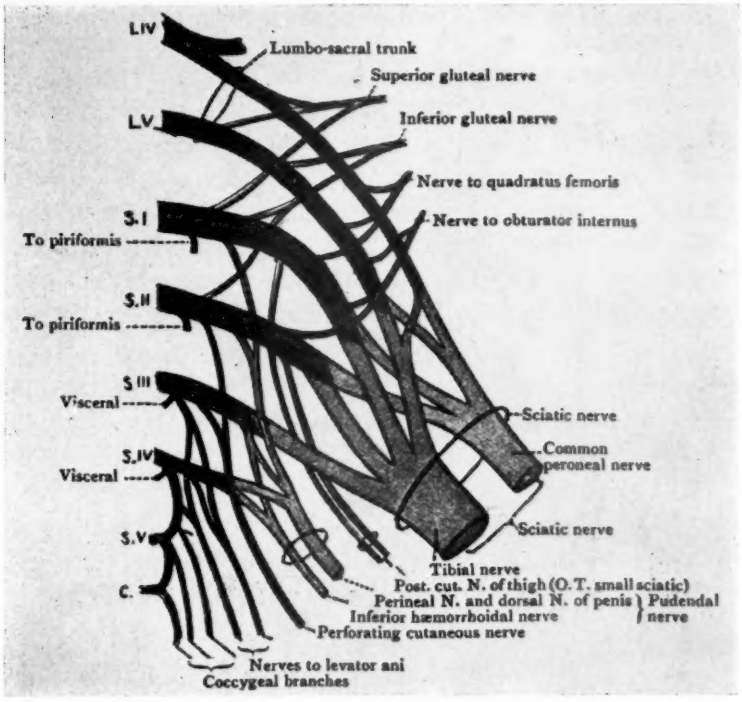

Fig. 3.—The lumbosacral plexus of nerves. The extent of the peripheral sympathetic denervation obtained by severing cephalically the lumbar sympathetic nerve at point *B* corresponds to the terminal distribution of postganglionic neurons through this plexus. (From Cunningham's Manual of Practical Anatomy, ed. 8, New York, 1930, William Wood and Company.)

Only occasionally has the lumbar sympathetic nerve been sectioned cephalically at point *C*. When performed at this level, the position of the clip has been within zone *C*, and the extent of the denervation is depicted in Fig. 2, *C*. The lateral four toes and corresponding portion of the foot and the outer aspect for the leg have exhibited complete cutaneous sympathetic denervation. The great toe and inner aspect of the foot frequently have retained vasomotor and sudomotor function. The extent of the complete

sympathetic denervation corresponds segmentally to the terminal distribution of postganglionic sympathetic neurons through the fifth lumbar spinal nerve and the sacral plexus.

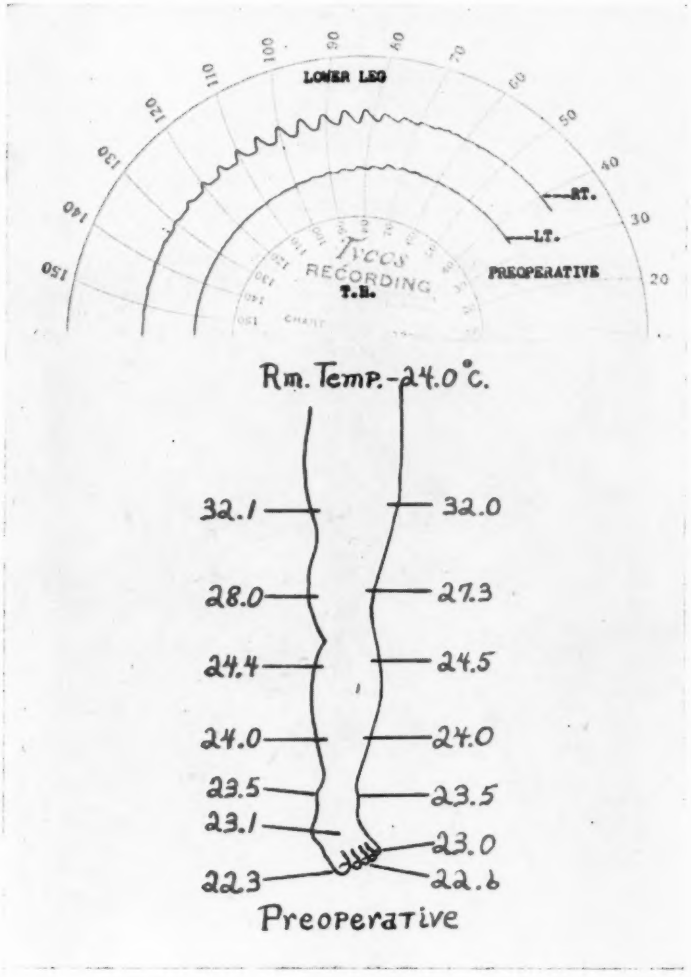

Fig. 4.—Case 1. Preoperative oscillometric readings taken at each supramalleolar level, and skin temperatures recorded at various points throughout each lower extremity. Note that diminution in skin temperatures extends up to and includes the lower portion of the thigh.

This study has a very real and practical clinical application. In 1947 DeBakey, Burch, Ray, and Ochsner[1] published their paper on the application of the physiologic principle of hemometakinesia to the management of peripheral arterial disease. They established the basic tenet, that the most effective form of vasodilating therapy confines its activity to ischemic tissue; and, conversely, that a therapeutically induced generalized relaxation of vascular tissue may aggravate peripheral ischemia. Pearl[2] has demonstrated the latter physiologic response to Etamon specifically, while I[3] have observed a similar reaction to intra-arterial injections of Priscoline in cases of advanced peripheral arteriosclerosis.

This physiologic principle applies to all vasodilating therapy including lumbar sympathectomy. In a recent editorial on the value of lumbar sympathectomy in the management of peripheral arteriosclerosis, DeTakats[4] recognized the possibility of inducing gangrenous necrosis by performing a high lumbar sympathectomy when trophic changes reflect a seriously obstructed collateral circulation to the ischemic foot. Obviously, when arterial disease or its overt clinical manifestations are confined to the distal portion of an extremity, and particularly when an obstructed collateral circulation more or less rigidly curtails the available blood supply, it is not physiologic to stimulate the proximal portion of the extremity and tissues outside the extremity to compete with the ischemic distal portion.

Fig. 5.—Case 1. Arrows point to silver clips identifying the point where each lumbar sympathetic nerve was severed cephalically. On the right side the nerve was severed in the region of the intervertebral disc between the second and third lumbar vertebrae; on the left side the point of cephalic section was at the upper border of the third lumbar vertebra. Each clip is located within zone *A*.

Low lumbar sympathectomy is a descriptive term which has been used very loosely. With some overlapping, three distinct so-called low procedures are available. The following cases illustrate what can be accomplished by sectioning cephalically the lumbar sympathetic nerve at points *A*, *B*, and *C* and the clinical indications for performing a sympathectomy at these levels.

ZONE A

When the collateral circulation to the distal portion of an ischemic lower extremity is not obstructed and the femoral artery pulsates vigorously, sym-

pathectomy at the *A* level will suffice. Exceptions are those cases wherein irritation of peripheral vasosensory neurons is responsible for painful disability.[5]

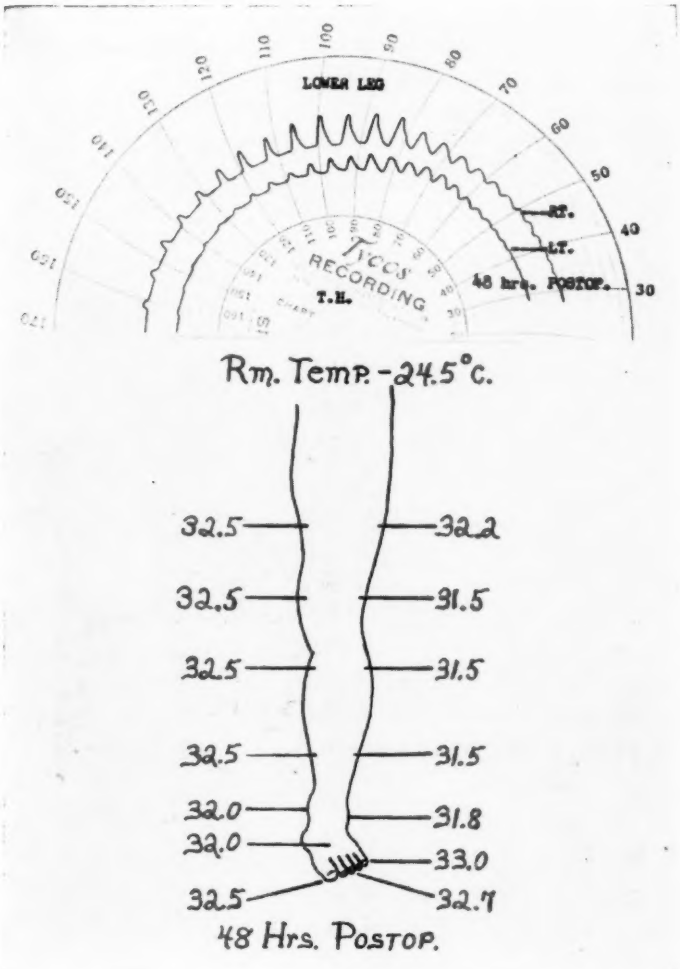

Fig. 6.—Case 1. Oscillometric readings and skin temperatures forty-eight hours following bilateral lumbar sympathectomy at level *A*. Compare with Fig. 4. Note the extensive cutaneous denervation up to and including the lower portion of the thigh. This type of vasomotor response to sympathetic denervation is characteristic of arteriolar and arterial spasm.

Case 1.—T. H., a 47-year-old white man, initially was observed in March, 1953. During the preceding three years walking had become increasingly difficult. At first he had experienced some fatigue in the calf of the left leg while playing golf. More recently, the fatigue had been supplanted by severe cramplike pain in both legs associated with numbness of the feet. Both feet were always cold. Walking capacity had finally become reduced to 100 yards and he was having difficulty in maintaining his balance. This man was a low-handicap amateur golfer, and the inability to negotiate his course was a severe blow to his morale. He was a heavy cigarette smoker; he was not diabetic; he gave no history of rheumatic fever or antecedent heart disease.

Both feet were palpably cold, hyperhidrotic, and exhibited a cyanotic tinge. There were no trophic changes or ulceration. The femoral arteries pulsated; the popliteal, dorsalis pedis, and posterior tibial arteries did not.

Fig. 4 includes the oscillometric tracing obtained from each leg and the thermocouple skin temperature readings from the left lower extremity, those from the right being equally diminished. Following the administration of a low spinal anesthetic, skin temperature readings rose to levels in excess of thirty degrees and oscillometric readings increased in magnitude.

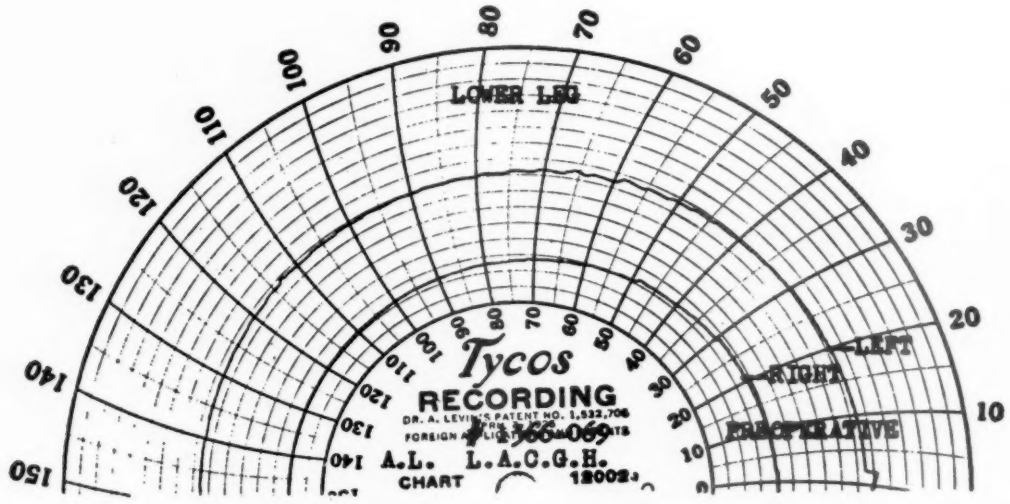

Fig. 7.—Case 2. Oscillometric tracings recorded preoperatively at each supramalleolar level.

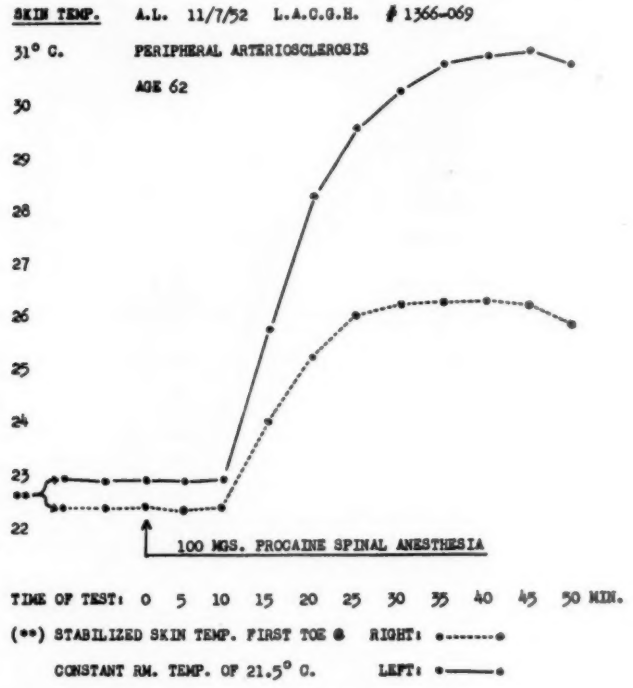
SKIN TEMP.
A.L. 11/7/52 L.A.C.G.H. # 1366-069
31° C.
PERIPHERAL ARTERIOSCLEROSIS
AGE 62
100 MGS. PROCAINE SPINAL ANESTHESIA
TIME OF TEST: 0 5 10 15 20 25 30 35 40 45 50 MIN.
(**) STABILIZED SKIN TEMP. FIRST TOE @ RIGHT:
CONSTANT RM. TEMP. OF 21.5° C. LEFT:

Fig. 8.—Case 2. Preoperative evaluation of the collateral vascular reserve. An excellent collateral circulation is present in the left lower extremity; in the right lower extremity the collateral circulation has been considerably impaired.

A diagnosis of obliterating arterial disease, probably thromboangiitis obliterans, complicated by arterial and arteriolar spasm, was made. A bilateral lumbar sympthectomy at the *A* level was performed. Fig. 5 shows the position of the silver clips as revealed in the postoperative x-ray film. Each clip is located within zone *A*.

An excellent immediate vasomotor response was obtained. Fig. 6 depicts the increase in oscillometric readings and rise in skin temperatures. The latter reached maximum vasodilatation levels throughout each sympathectomized extremity. Symptoms of coldness and numbness referable to the feet were relieved at once, and walking capacity subsequently increased. After he had recovered from the disabling effects of the operation per se, he resumed the game of golf. One year later he competed successfully in a four-day tournament.

Fig. 9.—Case 2. Arrows point to silver clips identifying level at which each lumbar sympathectomy was performed. On the left side the sympathectomy is "high"; on the right side the clip is in the region of the intervertebral disc between the third and fourth lumbar vertebrae falling within zone *B*.

ZONE B

The majority of patients who, for one reason or another, are candidates for low lumbar sympathectomy will fall within this category. The following are pertinent examples:

CASE 2.—A. L., a 62-year-old white man (number 1366-069), was admitted to the Los Angeles County General Hospital Oct. 24, 1952. For the previous several years he had been suffering from intermittent claudication in the right leg of progressively increasing severity. Latterly, the right foot had been very painful, cold, and numb. The left lower extremity was asymptomatic. He was not diabetic.

The right foot was atrophic and very pale. Both feet were palpably cold. Each femoral artery pulsated, but no pulsation could be detected in either popliteal, dorsalis

pedis, or posterior tibial artery. The oscillometer registered a trace of pulsation in the left leg but none in the right. (See Fig. 7.) A diagnosis of peripheral arteriosclerosis with serious involvement of the collateral circulation in the right leg was made.

The status of the collateral vascular reserve in each lower extremity was investigated in the constant temperature room. The results of this study are depicted in Fig. 8. It is obvious that while the collateral vascular reserve in the left lower extremity was of excellent quality, that in the right lower extremity was impaired.

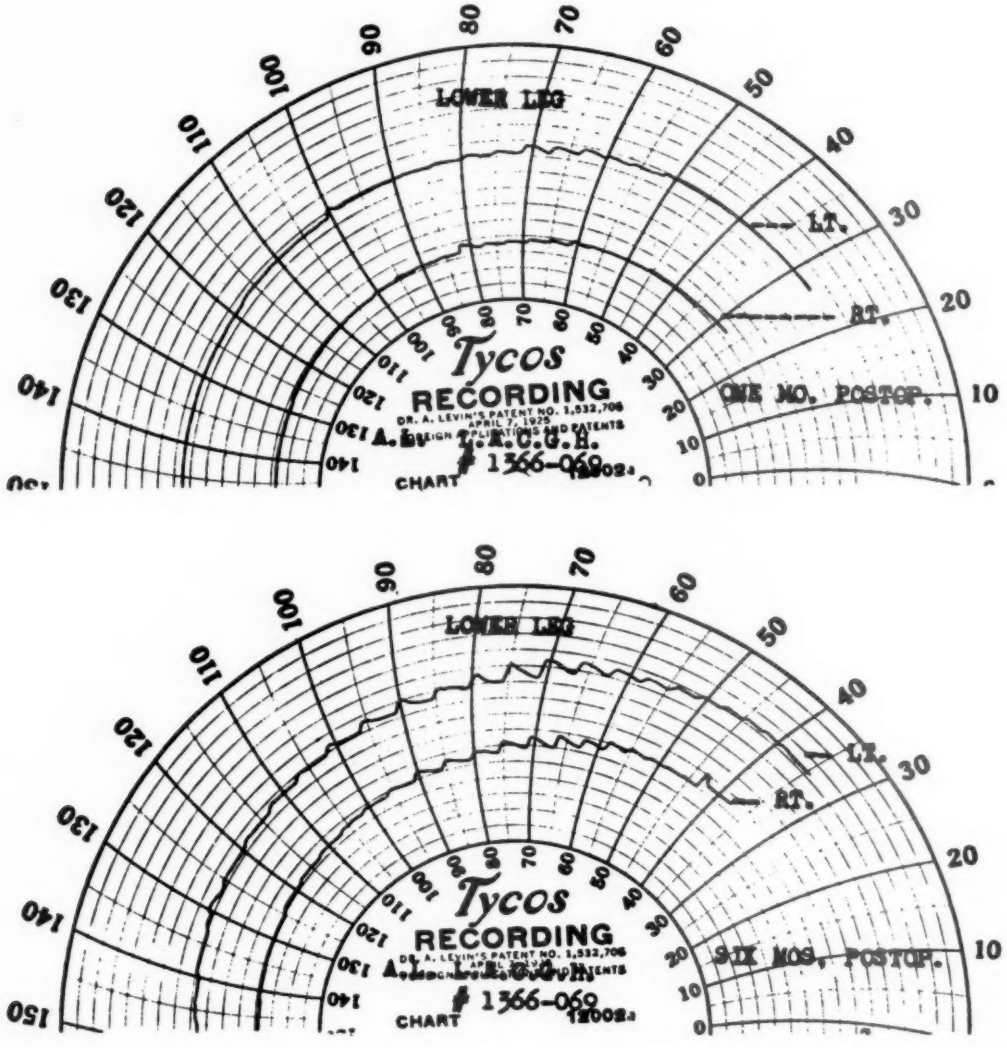

Fig. 10.—Case 2. Oscillometric tracings recorded at each supramalleolar level one and six months following a "high" left lumbar sympathectomy and a right lumbar sympathectomy at the *B* level. The pulsating vascular response in the right leg, indicative of the growth of collateral arteries, had not been anticipated.

The excellent collateral vascular reserve in the left lower extremity justified sympathectomy at a relatively high level. On the other hand, it was deemed inadvisable to perform a similar procedure on the right side. Instead, lumbar sympathectomy was performed here at a low level. Fig. 9 is a reproduction of the postoperative x-ray film localizing the position of the silver clips.

Fig. 11.

Fig. 12.

Fig. 11.—Case 3. Appearance of right foot on admission to hospital.

Fig. 12.—Case 3. Same foot as in Fig. 11, two weeks later. An abscess localized and drained spontaneously at the base of the gangrenous toes which have demarcated.

Fig. 13.—Case 3. Arrow points to silver clip which is at the lower margin of the third lumbar vertebra within zone *B*.

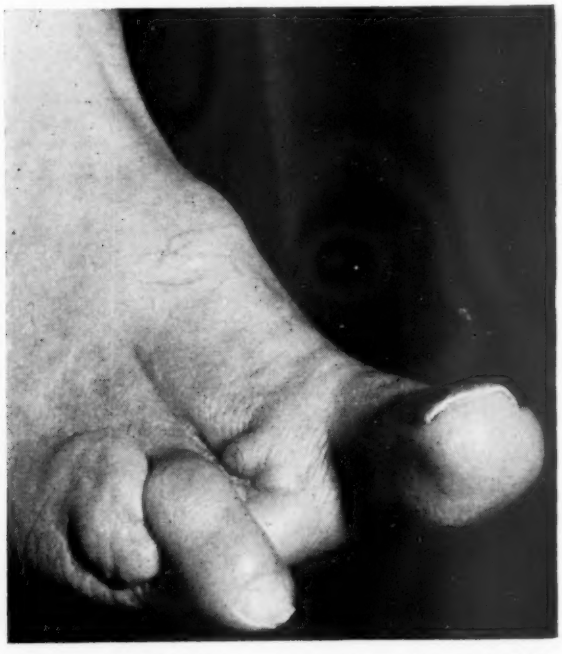

Fig. 14.—Case 3. Appearance of healed foot six months after amputation of gangrenous toes and a lumbar sympathectomy at the *B* level.

Postoperatively, there was slight sweat gland activity in the region of the right internal malleolus. However, this did not affect the clinical response, which was unexpectedly gratifying. Sensations of coldness, numbness, pain, and paresthesias in the right foot were relieved immediately. For the first six months of postoperative observation, a progressive increase in walking capacity occurred which paralleled a progressive increase in the magnitude of oscillometric readings. (See Fig. 10.) This was interpreted as evidence of the growth of a collateral circulation.[6] At the end of six months of observation, the patient had become rehabilitated to the point where he was able to obtain remunerative employment and was lost to the clinic.

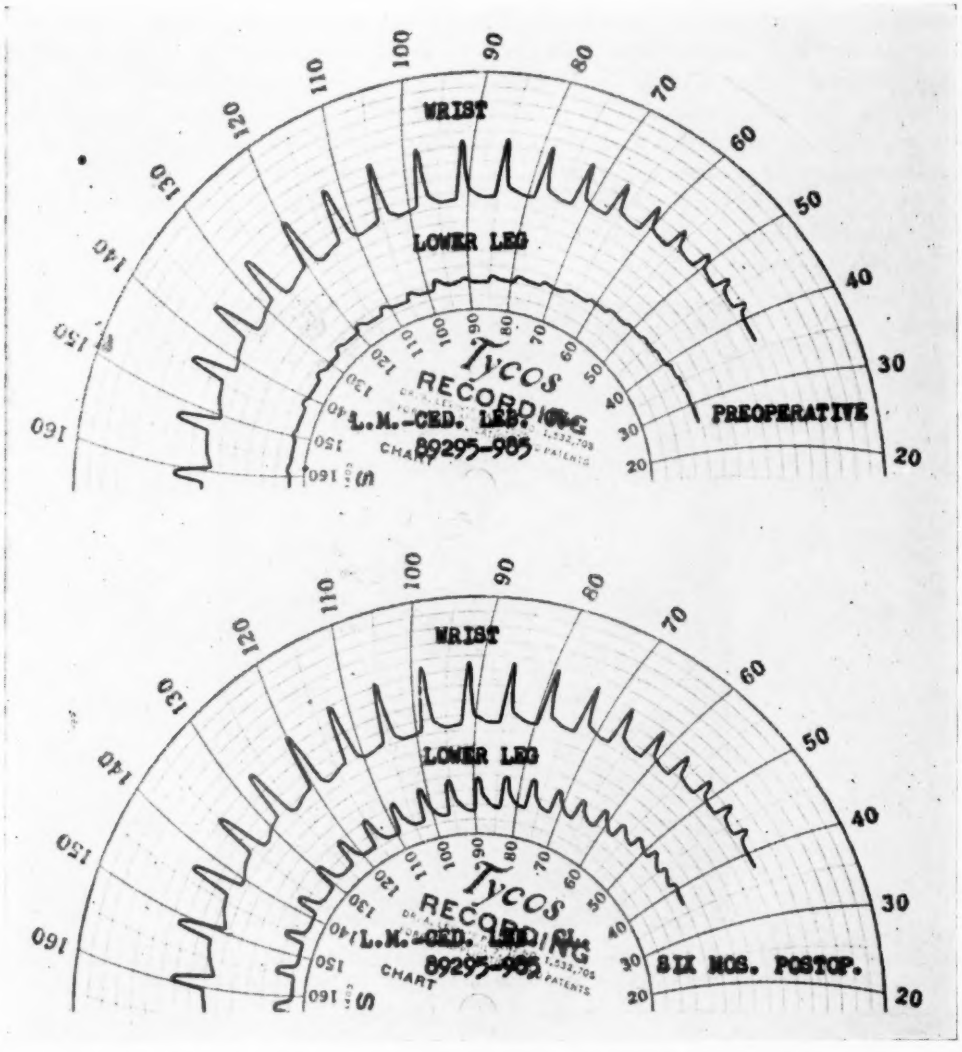

Fig. 15.—Case 3. Shows the marked increase in pulsation in the sympathectomized leg six months after lumbar sympathectomy at the *B* level.

Case 3.—L. M., No. 89295-985, a 68-year-old white man, was admitted to the Cedars of Lebanon Clinic Hospital Oct. 16, 1953. He was mildly diabetic and controlled by diet. Three months prior to admission, pus started to drain from a callus on the ball of the right foot. A few days prior to admission, the foot had become swollen and painful and a toe had become black.

Examination revealed an acute cellulitis of the right foot with frank gangrene of the third digit and impending gangrene of the second. (See Fig. 11.) Purulent material could be expressed from a sinus in the ball of the foot. The foot was palpably hot. Pulsation could be felt in the popliteal artery but not in the posterior tibial or dorsalis pedis arteries. The oscillometer registered four degrees of pulsation at the level of the lower forearm but only one-half degree at the level of the lower third of the leg.[7]

The patient was placed on large doses of penicillin supplemented with Erythromycin. Within two weeks an abscess localized and drained spontaneously at the base of the gangrenous toes. During this period the gangrenous toes demarcated. (See Fig. 12.) Approximately six weeks after admission the gangrenous toes were amputated and a lumbar sympathectomy performed to expedite healing of the defect in the foot. Pathologic examination revealed arteriosclerosis and a suppurative osteoarthritis involving the metatarsophalangeal joints. Fig. 13 is the postoperative x-ray film showing the level at which the lumbar sympathetic trunk was divided cephalically. The position of the silver clip falls within zone *B*. Sympathectomy was performed at this level because the clinically significant vascular disease was confined to the distal portion of the limb. Figs. 14 and 15 portray, respectively, the healed foot and the increased oscillometric readings registered six months later.

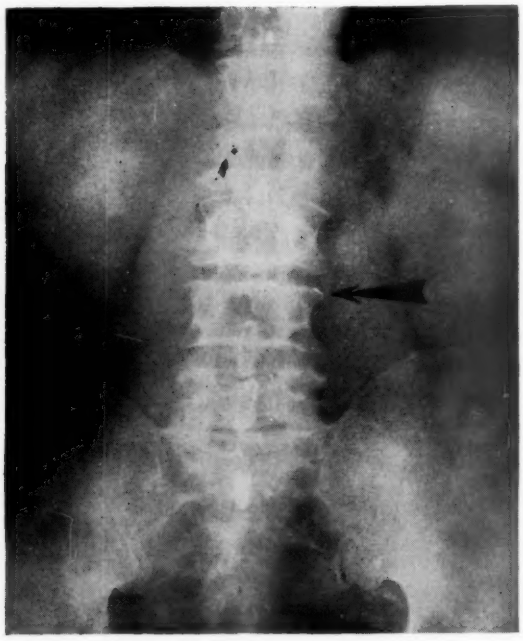

Fig. 16.—Case 4. Arrow points to the silver clip which is located near the intervertebral disc between the third and fourth lumbar vertebrae within zone *B*.

In the preceding two cases lumbar sympathectomies were performed at the *B* level because in one the collateral circulation partially was obstructed, while in the other the clinically significant vascular disease was concentrated in the distal portion of the extremity. In the following case, while the arterial disease involved the proximal as well as the distal portion of the limb, the clinical manifestations urgently requiring surgical correction were limited to the foot.

CASE 4.—J. F., No. 66715-131, a 63-year-old white man, was admitted to the Cedars of Lebanon Clinic Hospital in November, 1953. One month prior to admission the left fifth toe had become suddenly discolored and very painful. Subsequently the entire foot became blue, cold, and numb. During a period of several years prior to this admission he had suffered a total of three attacks of myocardial infarction.

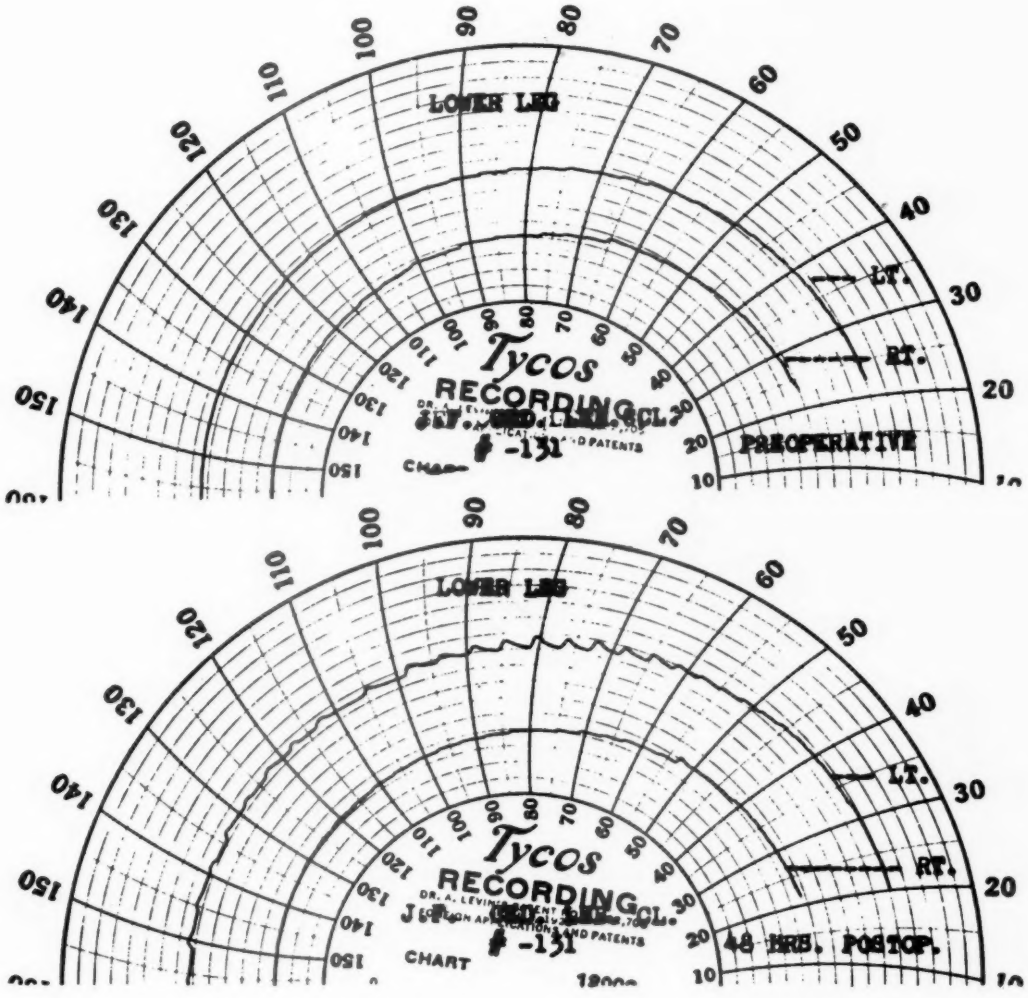

Fig. 17.—Case 4. Oscillometric tracings showing the characteristic pulsating vascular response which follows sympathetic denervation when arterial spasm is superimposed on arteriosclerosis.

The patient was not diabetic. The left fifth toe was discolored and exquisitely sensitive. The precise nature of the acute digital lesion was obscure, although gangrene seemed imminent. The entire foot was dusky, palpably cold, and hyperhidrotic. Pulsation could not be detected in either popliteal, posterior tibial, or dorsalis pedis artery, and the oscillometer registered only a trace of pulsation in each leg. The femoral arteries pulsated. Following an injection of 25 mg. of Priscoline into the left femoral artery, the skin of the foot assumed a healthy pink color and skin temperatures rose an average of 6° C.

Sympathetic denervation of an arteriosclerotic leg ordinarily would not have been considered in an individual who already had sustained three episodes of coronary artery thrombosis. However, in this particular instance, vasospasm superimposed on a coexisting arteriosclerotic process threatened the viability of the limb. Because the vasospastic complication was confined to the foot, sympathectomy was performed at the *B* level. Fig. 16 shows the position of the clip.

Following surgery the denervated foot was palpably warm, pink, and dry, and the oscillometer now registered a distinct pulse. (See Fig. 17.) Within a few days the nail of the fifth toe separated to reveal an ulcer of the subjacent bed. This apparently was the ischemic lesion that had precipitated the vasospastic complication. Within three weeks the toe had healed and the patient was discharged. Six months later this initial improvement had been maintained.

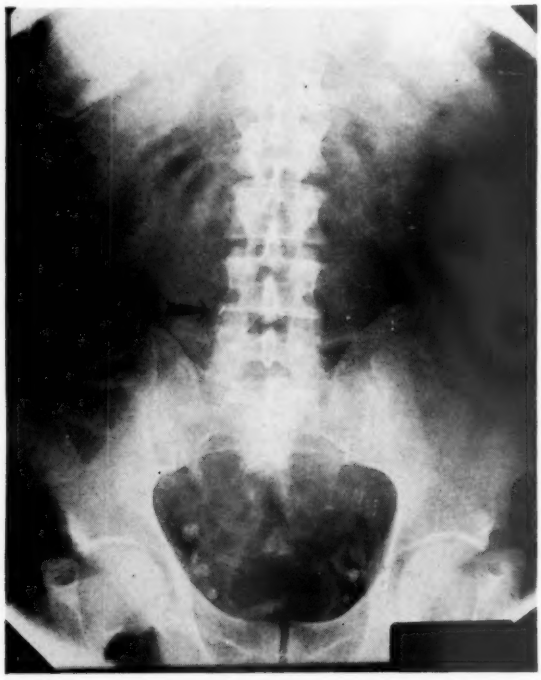

Fig. 18.—Case 5. Arrow points to silver clip which is located in the region of the intervertebral disc between the fourth and fifth lumbar vertebrae within zone *C*. Note the calcification of the pelvic arteries.

ZONE C

Lumbar sympathectomy at this level has only a very limited application. When an ischemic lesion involving the lateral four toes or corresponding portion of the foot threatens the integrity of the extremity, and when the collateral circulation to the ischemic foot is seriously obstructed, lumbar sympathectomy at this level may salvage the limb.

CASE 5.—E. B., a 66-year-old white man, was first observed Feb. 4, 1953. He had had moderately severe diabetes for fourteen years. For the previous several years his ability to walk had been impaired by intermittent claudication. For the previous three months he had suffered from increasingly severe pain in the right foot. The acute complication had started with an ulcer of the fourth toe. Despite intensive medical therapy

the ulcer had failed to heal and the pain had become excruciating. The pain now involved the entire foot, which burned and throbbed constantly and was most severe at night. Bed rest had become impossible.

The man was haggard from pain and loss of sleep. There was extreme dependent rubor of the foot, which was edematous and exhibited petechial hemorrhages. An indolent infected ulcer involved the interdigital surface of the fourth toe. The latter was exquisitely sensitive. Pulsation could not be detected in the popliteal, dorsalis pedis, or posterior tibial arteries, and the oscillometer registered no pulsation in the leg. The femoral artery pulsated. The patient seemed to be headed for a thigh amputation.

He was hospitalized for additional investigation. Daily he received an infusion of 500 c.c. of 0.2 per cent procaine and an injection of 25 mg. of Priscoline into the femoral artery. At the end of two weeks edema had disappeared, color had improved, and the diffuse causalgic pain had been relieved. The pain was now concentrated in the ulcerated toe, which showed no signs of healing. The collateral circulation obviously was involved by the obliterating process as evidenced by waxy pallor of the foot when it was elevated. Consequently, the most that could be offered in the way of a surgical denervation was a sympathectomy at the lowest feasible level. Fig. 18 shows the position of the silver clip in the region of the intervertebral disc between the fourth and fifth lumbar vertebrae.

There was no immediate striking improvement in regional circulation. However, within one week of the denervation, the ulcer showed signs of healing. Within the ensuing two months the ulcer healed, he was asymptomatic, and he was able to resume his occupation, which was that of a scientific instrument maker. Fourteen months have elapsed since then and he has been working steadily with no recurrence of ulceration or pain.

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LOWER THORACIC AND LUMBAR SYMPATHECTOMY FOR ARTERIOSCLEROTIC OBLITERATIVE DISEASE OF THE LOWER AORTA OR THE ILIAC ARTERIES

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SURGICAL methods for treating patients with obstruction of the major arteries supplying the legs and the viscera of the pelvis include sympathectomy to increase flow of blood through collaterals, thromboendarterectomy, and the excision of occluded segments. After excision, continuity has been restored by autogenous vein grafts, homogenous arterial grafts, or use of cloth tubes of Vinyon-N, Orlon, or other plastic material. Sympathectomy has usually included only the lumbar ganglia, and has been performed when clinical judgment and conventional studies of the circulation predict a good result. Usually lumbar sympathectomy has been considered contraindicated for patients with serious ischemia or impending gangrene. Thromboendarterectomy or excision of obstructed arteries and replacement by grafts or tubes can be performed only after an arteriogram has demonstrated a segmental obstruction. Although aortograms are relatively safe, there are occasional reports of complications including anuria, transverse myelitis, and mesenteric thrombosis. Indications for use of aortograms and for thromboendarterectomy or excision and grafting are not yet definitely established.

Recognition of the occurrence of segmental arterial obstruction is generally credited to Leriche. Leriche, Fontaine, and Dupertius[1] summarized their experiences by 1937. Believing that abnormal sympathetic vasoconstrictor reflexes originated in the diseased segment, they excised the area of occlusion and often observed improvement. Arterectomy and an associated interest in periarterial sympathectomy were gradually replaced by lumbar sympathectomy as clinical experience increased and as a better understanding of the anatomy and function of the sympathetic nervous system developed. This has been reviewed by one of us (K. S. G.[2]), emphasizing need for more extensive sympathectomies. Lilly,[3] Pearl,[4] Atlas,[5] and others have emphasized that a lumbar sympathectomy should include the first lumbar ganglion or the lowest thoracic ganglion. Most lumbar sympathectomies are performed for obstruction of the femoral artery or its peripheral branches. For them, lumbar sympathectomy effects fair or good improvement, best when treatment is undertaken early in the disease process. A few lumbar sympathectomies have

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been performed for iliac or aortic obstruction. It is not the purpose of this report to include treatment of obstructive disease of the femoral and peripheral arteries or to discuss lumbar sympathectomy.

Thromboendarterectomy for aortic or iliac obstruction was evidently first reported by J. Cid dos Santos.[6] In an excellent review, Lowenberg[7] credited Jacques Oudot[8] with the first successful excision and grafting of an aortic bifurcation. Coelho, Freeman, and Leeds[9] currently report discouraging results with thromboendarterectomy except when disease is limited to the terminal aorta or the iliac arteries. Julian and his associates[10] and DeBakey and associates[11] are encouraged with their early results of arterial homografts, aortic and iliac, in this area. Hufnagel[12] and Shumacker, Harris, and Siderys[13] have used plastic cloth tubes. Nevertheless, a significant risk of loss of limb or of operative mortality is associated with these major procedures. Although homografting seems well indicated for aortic aneurysm, its use in this less serious form of vascular disease does not seem established.

The purpose of this study is to determine results of use of a sympathectomy extended high enough to denervate the collateral vessels of the lower aorta and the iliac arteries, using this sympathectomy for the form of obstructive disease in which thromboendarterectomy or arterial grafting is now being tried.

DIAGNOSIS AND GROUPING OF PATIENTS

Lower thoracic and lumbar sympathectomy was first employed for segmental terminal aortic and iliac obstructive disease in 1949. Earlier these patients had been treated conservatively. Satisfactory equipment and methods for using long film aortograms[14] were not installed and perfected until 1952. Before 1952, a diagnosis of segmental obstruction was made on a clinical basis, a history of claudication originating in the thighs and pelvis or referred there from the claves, absence of pulsation of one or both femoral arteries and yet adequate circulation to maintain viability of the feet. Signs of severe ischemia of the feet such as would accompany ascending obliteration of the femoral pulse excluded patients from this tentative diagnosis. A definite diagnosis of segmental iliac or lower aortic obstruction was established by palpation of the aorta and iliac arteries, retroperitoneally, during sympathectomy. In each instance the clinical diagnosis proved correct. Since 1952, aortograms have been obtained before operation, using films thirty-six inches in length to visualize the aorta, iliac and femoral arteries. The roentgenologic demonstration of a segmental iliac or terminal aortic obstruction has not altered our recommendation for sympathectomy. Thromboendarterectomy has not been performed for patients with fair circulation through collaterals. As yet, no segmental obstruction has been treated by resection and replacement using a graft or tube.

Of twenty-four patients treated since 1949, nineteen with progressive symptoms but with adequate collateral circulation were treated by thoracolumbar sympathectomy. The remaining five had resting ischemic pain, patchy cyanosis, marked pallor on elevation, marked dependent rubor, and other signs

and symptoms of impending gangrene. Among other operative procedures, thromboendarterectomy was performed for four of these. Results for the twenty-four patients will be presented in four groups: Group I, eight patients with unilateral lower thoracic and lumbar sympathectomy; Group II, five patients with a high sympathectomy on one side and a conventional lumbar sympathectomy for the opposite limb; Group III, six patients with bilateral high sympathectomy; and Group IV, the five patients with multiple operations for impending gangrene.

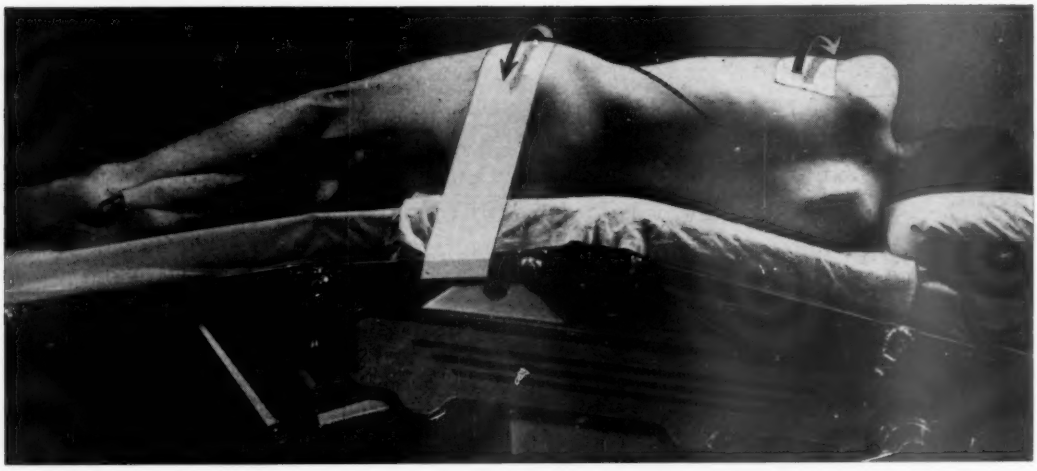

Fig. 1.—For lower thoracic and lumbar sympathectomy the patient is placed in a lateral position, hyperextended and with the shoulder pulled forward and the hip backward using adhesive tape traction.

OPERATIVE TECHNIQUE

The technique developed in 1949 is a simplification of the conventional thoracolumbar splanchnicectomy (Smithwick[15]) and a modification of the transthoracic approach described by one of us (K. S. G.[16]) and employed in patients with hypertension. The patient (Fig. 1) is placed in a lateral position with the shoulders and chest rotated forward to bring the thoracic ganglia into convenient view, and the hip rotated backward to aid visualization of the lumbar ganglia lying beyond the psoas muscles. Exposure is aided by removing the twelfth rib. Incision through the periosteum and the abdominal muscles allows development of the retropleural and retroperitoneal spaces. The thoracic and the abdominal cavity are not entered. The aorta and the iliac artery are palpated, retroperitoneally, to confirm the preoperative diagnosis. The lower thoracic ganglia, up to or including the ninth thoracic, and all of the lumbar ganglia are removed. The splanchnic nerve is left intact unless there is a coexisting hypertension.* A temporary catheter is left in the retropleural space until the skin is closed, then aspirated and removed. The area of loss of sweating following this operation is indicated in Fig. 2.

*An additional patient, not reported in detail, had bilateral thoracolumbar sympathectomy and splanchnicectomy for hypertension and peripheral femoral obstruction. The femoral arteries were palpable before operation. The limbs remained viable until death from chronic cardiac failure after four years.

UNILATERAL LOWER THORACIC AND LUMBAR SYMPATHECTOMY

Eight patients with iliac or terminal aortic obstruction had high sympathectomy on one side and no operation on the other. Only one (N. U. P.) was a female. Of the eight, the opposite femoral pulse was palpable in six. An aortogram of one (patient F. H. H.) is illustrated in Fig. 3. Neither femoral pulse could be felt in two patients. For these two, operation was performed on the side of the most pronounced symptoms and with findings of greatest impairment

Fig. 2.

Fig. 3.

Fig. 2.—A starch-iodine-heat sweating test of Patient A. B. W. obtained nine days following right lower thoracic and lumbar sympathectomy. There is no sweating of the right lower abdomen, groin, or leg.

Fig. 3.—A long film aortogram obtained in Patient F.H.H. reveals a filling defect from the right terminal aorta through the length of the right common iliac artery to the external iliac artery. The external iliac and femoral arteries visualize faintly by Urokon sodium carried through collaterals. The aorta and left iliac and femoral vessels are patent.

of circulation. Results during the five years are summarized in Table I. Each patient is well satisfied and each has a warm foot on the side of operation. The opposite limb remains normal in four. The four who list satisfaction for the leg not sympathectomized as only fair have developed increasing claudication and other symptoms, but do not yet consider their trouble sufficient to return for sympathectomy. Only two patients have had significant

improvement of the distance they walk before claudication, Patients L. R. N. and E. L. C. Each states that he can walk indefinitely at a slow pace. Persistence of claudication of the sympathectomized leg in the remainder is accepted as a necessary and minor inconvenience. One patient, E. L. C., has developed sufficient collateral circulation that femoral, popliteal, posterior tibial, and dorsal pedis pulses are now palpable sixteen months after sympathectomy. Measurements of the skin temperature gradient verify persistence of increase in warmth. Oscillometric readings, however, remained low or absent, less than ½ point, in each patient except E. L. C., who now has a reading of 2 points. One patient, F. H. O., died of a coronary occlusion at thirty-four months. The remainder are all carrying on relatively normal occupations without a significant handicap. There was no operative mortality or loss of limb.

TABLE I. UNILATERAL LOWER THORACIC AND LUMBAR SYMPATHECTOMY: EIGHT PATIENTS WITH ILIAC OR TERMINAL AORTIC OBSTRUCTION

PATIENT	AGE (YR.)	SYMPTOMS (MO.)	CLAUDICATION SITE	CLAUDICATION BLOCKS	FOLLOW-UP (MO.)	CLAUDICATION SITE	CLAUDICATION BLOCKS	TEMPERATURE (FOOT)	SATISFACTION, LEG: SYMPATHECTOMY	SATISFACTION, LEG: OTHER
Other femoral pulse palpable:										
L. R. M.	52	2	Right calf	½	54	Foot	5	Warm	Yes	Fair
E. B. K.	58	9	Right hip	1	44	Left hip	½	Warm	Yes	Normal
L. E. A.	62	9	Left calf	2	23	Left calf	2	Warm	Yes	Normal
N. U. P.	52	24	Right hip	1	20	Right hip	1¼	Warm	Yes	Fair
E. L. C.	53	72	Right hip	2	16	Hips	5	Warm	Yes	Normal
F. H. H.	54	3	Left hip	2	6	Left hip	1	Warm	Yes	Normal
Neither femoral pulse palpable:										
F. H. O.	65	144	Hips	2	34*	Hips	2	Warm	Yes	Fair
B. N. L.	64	60	Hips	1	18	Hips	2	Warm	Yes	Fair

*Died, coronary occlusion.

BILATERAL LOWER THORACIC AND LUMBAR SYMPATHECTOMY

Six patients with obstruction at the terminal aorta or in the iliac artery evidenced their satisfaction by returning for a second high sympathectomy for the opposite limb. One, A. B. W., was a female. Neither femoral pulse was palpable in these patients. Results during the five years are summarized in Table II. Each patient is well satisfied with the result of operation for each limb. Persistence of increased warmth is evidenced by measurements of skin temperature gradient. It is noted that claudication was more prompt before and after operation in this group than was the case for patients in Table I. Nevertheless, persistence of claudication is accepted by each patient. They have adjusted activities to minimize the inconvenience. Oscillometric readings remained ½ point or less. One patient, R. S. M., developed chronic cardiac failure two years after the sympathectomy and died at fifty-nine months. There had been no difficulty with the legs. There was no loss of limb or operative mortality in this group.

TABLE II. BILATERAL LOWER THORACIC AND LUMBAR SYMPATHECTOMY: SIX PATIENTS WITH BILATERAL ILIAC OR TERMINAL AORTIC OBSTRUCTION

PATIENT	AGE (YR.)	SYMPTOMS (MO.)	CLAUDICATION		FOLLOW-UP (MO.)	CLAUDICATION		TEMPERATURE (FOOT)	SATISFACTION	
			SITE	BLOCKS		SITE	BLOCKS		1ST OPERATION	2ND OPERATION
A. B. W.	61	24	Hips	1	64	Hips	2	Warm	Yes	Yes
R. S. M.	63	18	Left hip	½	59*	Hips	1	Warm	Yes	Yes
W. S. R.	53	12	Right hip	⅙	36	Right hip	⅓	Warm	Yes	Yes
N. G. N.	56	8	Hips	⅓	35	Hips	⅓	Warm	Yes	Yes
M. G. B.	53	18	Hips	½	25	Hips	½	Warm	Yes	Yes

*Death, chronic cardiac.

UNILATERAL LOWER THORACIC AND LUMBAR SYMPATHECTOMY, CONVENTIONAL LUMBAR SYMPATHECTOMY FOR OPPOSITE LIMB

Five patients with iliac or terminal aortic obstruction had a high sympathectomy of the limb with absent femoral pulse and a conventional lumbar sympathectomy for the opposite limb, femoral pulse palpable. An aortogram of one, Patient E. W. P., indicates complete iliac obstruction and poor retrograde femoral filling on the side of the high sympathectomy, incomplete segmental obstruction on the right, the side of the conventional sympathectomy (Fig. 4). One, P. G. C., was a female. Results are summarized in Table III. Four of the five patients are well satisfied and each has a warm foot. One of these four, J. C. H., died of a coronary occlusion at fifteen months but had had no other trouble. The remaining patient, R. L. E., was well satisfied with the result of the lower thoracic and lumbar sympathectomy even though he is now a bilateral amputee. The high sympathectomy was first performed at this hospital. One year afterward a conventional lumbar sympathectomy was performed elsewhere. Six months later this limb was amputated. He gives his satisfaction with the high operation as good since he used this limb forty-five months before pain and gangrene developed requiring amputation. This stump is the better one for an artificial limb. This patient is the only one of the nineteen treated by the high sympathectomy who has as yet required amputation.

TABLE III. UNILATERAL LOWER THORACIC AND LUMBAR SYMPATHECTOMY: FIVE PATIENTS WITH UNILATERAL ILIAC OBSTRUCTIVE DISEASE WHO ALSO HAD CONVENTIONAL LUMBAR SYMPATHECTOMY FOR OPPOSITE LIMB

PATIENT	AGE (YR.)	SYMPTOMS (MO.)	CLAUDICATION		FOLLOW-UP (MO.)	CLAUDICATION		TEMPERATURE (FOOT)	SATISFACTION	
			SITE	BLOCKS		SITE	BLOCKS		HIGH OPERATION	LUMBAR
P. G. C.	41	18	Left calf	1	62	Left calf	½	Warm	Yes	Yes
R. L. E.	58	3	Left calf	½	46	Left hip	⅛	Warm	Yes*	No†
H. H. R.	60	4	Calves	Steps	32	Calves	1	Warm	Yes	Yes
J. C. H.	61	18	Calves	Steps	15‡	Calves	1	Warm	Yes	Yes
E. W. P.	42	12	Left hip	⅓	8	Feet	1	Warm	Yes	Yes

*Until amputation at forty-five months.
†Amputation at six months.
‡Died of coronary occlusion.

OPERATIONS FOR ILIAC OR AORTIC OBSTRUCTION AND IMPENDING GANGRENE

Five patients with obstruction of the terminal aorta or the iliac arteries or both differed from the preceding nineteen since they were admitted to the

hospital as emergency problems because of marked resting pain, marked patchy cyanosis, and pallor of one or both feet or limbs and with other evidences of serious ischemia. The admission diagnosis was impending gangrene. Treatment and results are indicated in Table IV. Four of the five patients had amputations and one of the four died. The sequence of operations, including

Fig. 4.

Fig. 5.

Fig. 4.—A long film aortogram obtained in Patient E. W. P. indicates complete obstruction of the left common and external iliac arteries with faint outline of the femoral artery. On the right there is an incomplete segmental obstruction of the common iliac artery with excellent visualization of the external iliac and femoral arteries. High sympathectomy was performed on the left and conventional lumbar sympathectomy on the right.

Fig. 5.—A long film aortogram, obtained in Patient L. C. H. eighty-one days after removal of a fresh thrombus which had extended up to the level of the renal arteries and thromboendarterectomy of the terminal aorta and the left common and external iliac arteries, reveals complete patency. The right common and external iliac arteries do not visualize and there is no filling of the femoral. The obstruction of the right common and external iliac arteries was treated less successfully by thromboendarterectomy performed three days after this aortogram.

thromboendarterectomy in three, was discouraging and debilatating. Thromboendarterectomy of the lower aorta and right iliac artery was successful in the fifth patient, T. E. G., in that amputation was avoided, pulses are full, and no secondary operation has as yet been necessary during a nine-month follow-up period. However, he experiences claudication after walking 100 yards. Unfortunately, only this patient had a short segment of obstruction,

upper right common iliac artery. The other four had long segments of obstruction including the external iliac artery to the femoral, and two of these patients, S. E. F. and L. C. H., also had recent thrombosis of the lower abdominal aorta extending up to the renal arteries. In only one instance (Fig. 5) was thromboendarterectomy involving the external iliac artery successful in restoring a pulse. Removal of a fresh aortic thrombus and the diseased intima and old thrombus of the terminal aorta, common and external iliac arteries on the left as evidenced by this postoperative aortogram restored all pulses to an amputation site below the knee. This aortogram preceded thromboendarterectomy subsequently performed on the right side. On the right, femoral pulse was not restored and gangrene required amputation below the knee.

TABLE IV. OPERATIONS FOR ILIAC-AORTIC OBSTRUCTION AND IMPENDING GANGRENE: FIVE PATIENTS, RESTING PAIN AND PATCHY CYANOSIS, MARKED ISCHEMIA AND DEPENDENT RUBOR

PATIENT	AGE (YR.)	OPERATIONS	INTERVAL (OPERATIVE DAYS)	FINAL DIAGNOSIS	OUTCOME
Lower thoracic and lumbar sympathectomy:					
S. E. F.	64	Left peripheral nerve crush	--	Atherosclerosis, iliac arteries; recent thrombosis, aorta	Bilateral amputation Death
		Left high sympathectomy	12		
		Left mid-thigh amputation	5		
		Right mid-thigh amputation	10		
Sympathectomy followed by thromboendarterectomy:					
R. C. S.	57	Left high sympathectomy	--	Atherosclerosis, left iliac artery	Left amputation
		Left iliac thromboendarterectomy	150		
		Left mid-thigh amputation	62		
T. M. M.	53	Bilateral lumbar sympathectomy	--	Atherosclerosis, terminal aorta and iliac	Right amputation; left leg poor
		Endarterectomy, iliacs and aorta	60		
		Right mid-thigh amputation	21		
		Right débridement of stump	29		
Thromboendarterectomy alone:					
L. C. H.	56	Endarterectomy, iliacs and aorta	--	Atherosclerosis, iliac and terminal aorta; recent thrombosis lower aorta	Left amputation; right amputation
		Left amputation, below knee	4		
		Closure wound disruption	11		
		Skin grafting, abdominal wound	27		
		Right iliac thromboendarterectomy	42		
		Right amputation	11		
T. E. G.	53	Right endarterectomy, iliac and aorta	--	Atherosclerosis, right iliac	Recovery; good pulses

DISCUSSION

Excision of the lower thoracic and all of the lumbar ganglia has given encouraging results in the treatment of nineteen patients with unilateral or bilateral obstruction of the terminal aorta or iliac arteries and with viable limbs. Usually the terminal aorta and the iliac arteries have been involved, often also the external iliac. There has been no operative mortality and but one limb required amputation, this four years after sympathectomy. It is recognized that patients with this type of aortic and iliac obstruction and with collateral circulation sufficient to maintain viability, who were seen before

1949 and treated without operation, did fairly well. Results of this study indicate that high segmental obstruction is less serious than the more common atherosclerosis involving arteries lower in the leg. Results of high sympathectomy for high segmental obstruction seem better than the fairly good results of conventional lumbar sympathectomy as commonly used for more peripheral arterial obstruction. Results of either operation are best as judged by satisfaction of the patient and warmth of limb, poorest as judged by incidence of relief from claudication or improvement of oscillometric readings.

Relief from claudication and return of full pulses have evidently been achieved more frequently by those using aortic bifurcation and common iliac grafts in similar patients. However, they report a greater operative mortality and a higher incidence of loss of limb. Grafting and thromboendarterectomy apparently give poorest results in patients with obliterative disease extending into the external iliac artery, a situation present in some of our patients treated by high sympathectomy. The results of high sympathectomy are now reported for comparison with results of others using arterial grafting, thromboendarterectomy, or the conventional lumbar sympathectomy. Comparison of results of these different operations after five years or longer should permit a formulation of indications for each operation. At present, lower thoracic and lumbar sympathectomy continues as our preference for most patients meeting indications for operation and yet having no symptoms or findings of impending gangrene. This preference continues even though our experience with aortic homografts to replace aneurysms of the abdominal aorta and including the upper iliac arteries has been excellent. The problem of handling the smaller external iliac arteries or of grafting to the femoral artery would be more difficult. Also it is obvious that the prognosis with obstruction by atherosclerosis with or without surgical treatment is much more favorable than that of aortic aneurysm without surgical treatment.

As indicated by results of treatment in the five patients with impending gangrene (Table IV), no operation or combination of operations has been entirely successful. Where amputation was avoided, the flow of blood through collateral vessels about the long areas of obstruction and intimal stripping has certainly played an important role, since full return of pulses was achieved in only two patients. In this group of patients with severe resting pain and patchy areas of pallor or cyanosis, a direct surgical approach into the arteries seems best indicated. Two of the five patients may have had their lives saved by removal of the ascending fresh thrombosis which had extended upward to the renal arteries. Certainly sympathectomy alone does not seem indicated as a primary operation. Instead, its use has been that of an adjunct to treatment. Better techniques for preventing thrombosis following endarterectomy particularly when this must be extended into the external iliac artery, or for grafting with an anastomosis to the femoral artery, would be helpful.

It should be emphasized that an aortogram has not been recommended for every patient with absence of a femoral pulse and with findings suggesting a high segmental obstruction. Also every patient for whom this diagnosis has been confirmed by an aortogram has not been considered a surgical problem.

Indications for an aortogram have been the suspicion of a segmental obstruction in patients with progressive symptoms which are not responding to conservative management. Of those whose study included an aortogram, high sympathectomy has been recommended only if the obstruction seems long and the collateral circulation as judged by poor filling of the femoral vessels seems inadequate.

CONCLUSION

Use of lower thoracic and lumbar sympathectomy for patients requiring operation because of aortic and iliac obstructive disease has given satisfactory results during a five-year follow-up period.

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THE SYME AMPUTATION IN PERIPHERAL ARTERIAL DISEASE

A Report of Six Cases

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INTRODUCTION

SINCE the advent of the sulfonamide drugs and the antibiotics, there has been a major change in our concept of, and confidence in, the surgeon's ability to operate successfully in or near tissues rendered ischemic by obliterative arterial disease. The antibiotics have helped the healing processes by suppressing minor infections. Prior to their advent the occasional serious consequence of the unsuccessful attempt at such an operation was a fatal infection. It is natural, therefore, that the transmetatarsal and even the lower leg amputation for diabetic and arteriosclerotic gangrene were, prior to ten years ago, used but rarely.

A description of the principles underlying the successful performance of an amputation in the foot in ischemic tissue, namely, the transmetatarsal amputation, was published by McKittrick and associates[1] five years ago. They reported as a major factor in their success an ability safely to pursue a policy of allowing infection and ischemic necrosis to stabilize for many days or weeks under the influence of antibiotics prior to performing the amputation. It is, we believe, important to realize that once this principle has been recognized as sound in closed amputations in the foot, it applies not only to those at the transmetatarsal level but at other points which may be dictated by the proximal level of forbidding ischemia.[2]

The application of such principles to the performance of amputations 1 cm. proximal to the lower articular surface of the tibia using a long flap of the posterior and plantar skin of the heel, first described by Syme,[3] has, in our experience, under special circumstances, been highly successful in six instances. Since peripheral arterial deficiency has in the past been considered a prime contraindication to the Syme amputation,[4] it is a description and discussion of this experience that are the mission of the present paper.

Read at the eighth annual meeting of the Society for Vascular Surgery, San Francisco, June 20, 1954.

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CASE REPORTS

CASE 1.—J. P. V., West Roxbury V.A. Hospital, R#31256. Aged 58 years. Admitted Aug. 24, 1950, discharged Dec. 18, 1950.

Diagnosis.—Arteriosclerosis obliterans.

History.—3 years before—lost nail left great toe.

1½ years before—black spot left great toe.

4 months before—pain in left foot.

3 months before—left lumbar sympathectomy.

2 months before—left great toe amputated—failure to heal.

Local Examination.—Left lower extremity: Lowest palpable pulse was the popliteal. Marked rubor on dependency and a necrotic, partially granulating, open amputation wound of left great toe. Oscillations in left calf were a trace only.

Right lower extremity: Lowest palpable pulse was the popliteal. Moderate ischemic rubor on dependency.

Clinical Course.—Sept. 6, 1950—left transmetatarsal amputation—performed well proximal to lesion but bleeding subnormal.

Oct. 10, 1950—wound broke open, showing necrotic base.

Nov. 2, 1950—left Syme amputation—bleeding good.

16 days postoperative—walking on crutches.

21 days postoperative—measured for prosthesis.

27 days postoperative—discharged from hospital having healed per primam.

30 days postoperative—prosthesis procured and use begun.

6 weeks postoperative—prosthesis worn full time.

2 months postoperative—back to work as laborer.

1 year postoperative—intermittent claudication in right calf started.

December, 1952—right lumbar sympathectomy.

Last Follow-up.—3 years after left Syme amputation. Walks without limp or support. Working as laborer. Intermittent claudication right calf persists. Syme's stump well healed. Lowest pulses bilaterally are the popliteals.

CASE 2.—A. S., West Roxbury V.A. Hospital, R#38515. Aged 57 years. Admitted Nov. 22, 1951, discharged Feb. 13, 1952.

Diagnosis.—Arteriosclerosis obliterans. Diabetes mellitus.

History.—15 years before—diagnosis of diabetes mellitus made.

4 days before—spontaneous area gangrene left great toe.

Local Examination.—Left lower extremity: Gangrene medial aspect great toe with purulent exudate. Cellulitis of entire toe extending onto the foot. Lowest palpable pulse was the popliteal. Calf oscillations 3+.

Right lower extremity: Normal appearance. Lowest palpable pulse was popliteal. Calf oscillations 3+.

Clinical Course.—Nov. 30, 1951—transmetatarsal amputation—left.

Dec. 10, 1951—area necrosis appeared in stump and progressively enlarged during next 2 weeks.

Dec. 27, 1951—Syme amputation, left—bleeding in the wound was poor.

1 week postoperative—fluid aspirated from under flap.

4 weeks postoperative—up on crutches.

7 weeks postoperative—discharged with stump healed per primam.

4 months postoperative—walking with prosthesis using only one crutch.

Last Follow-up.—February, 1953, 2⅓ years after left Syme amputation. Walks well with prosthesis using a cane occasionally. Keeps prosthesis on all day. No limp, no troubles with stump. Can walk around house without prosthesis. Is as active as he was before he developed the gangrene.

CASE 3.—R. S., West Roxbury V.A. Hospital, R#39343. Aged 65 years. Admitted Jan. 9, 1952, discharged April 4, 1952.

Diagnosis.—Buerger's disease.

History.—30 years before—onset Buerger's disease.

8 years before—right lumbar sympathectomy.

8 years before—amputation right great toe for gangrene.

2 years before—pain in left foot—left lumbar sympathectomy.

1 month before—amputation left middle toe for gangrene which had failed to heal.

Local Examination.—Lowest palpable pulses were in popliteal spaces bilaterally. Healed amputation right great toe; unhealed crusted painful amputation left middle toe; ischemic rubor of both feet on dependency.

Clinical Course.—Jan. 16, 1952—Syme amputation, left, performed after making a preliminary incision for a transmetatarsal amputation and encountering a suppurative tenosynovitis.

10 days postoperative—up on crutches.

25 days postoperative—wound healed, no fluid. Measured for prosthesis.

8 months postoperative—first walked on prosthesis.

Last Follow-up.—March, 1954, 2 years after Syme amputation. Has been walking with cane using prosthesis ever since it was provided 16 months ago. He is abnormally timid, which was the reason he did not wear the prosthesis for 8 months. For some reason he does not walk at all without it. He is active but does not work. He has not done so for 10 years. He now has a small necrotic ischemic lesion on dorsum of the right foot which is requiring hospital care. Pulses in lower extremities same as 2 years ago; namely, popliteals palpable, none below.

CASE 4.—J. N. R., Cushing V.A. Hospital, R#41437. Aged 33 years. Admitted Dec. 26, 1952, discharged June 24, 1953.

Diagnosis.—Buerger's disease.

History.—9 years before—shrapnel wound left knee—frostbite left foot.

4 years before—left lumbar sympathectomy.

3 years before—ischemic lesion left foot. Nodules of phlebitis migrans left lower leg. Left lower leg amputation. Pathologic report: thromboangiitis obliterans, chronic granulomatous phlebitis.

1¼ years before—abscess amputation stump.

1 year before—left Gritti-Stokes amputation.

2 weeks before—necrotic lesion dorsum right foot.

Local Examination.—Right lower extremity: Lowest pulse was popliteal. Oscillations in calf only a trace. Necrotic lesions first and second toes.

Left lower extremity: Well-healed Gritti-Stokes amputation present. Femoral pulse palpable.

Clinical Course.—Jan. 5, 1953—débridement first and second toes, right.

Jan. 8, 1953—right lumbar sympathectomy.

Jan. 22, 1953—amputation first and second toes, right.

Feb. 9, 1953—skin grafts to stumps.

Feb. 26, 1953—Syme amputation, right—bleeding good.

3 weeks—good postoperative—up on crutches. Slight drainage from central portion of suture line.

7 weeks postoperative—received prosthesis, limited use of it.

4 months postoperative—walking full time with prosthesis.

Last Follow-up.—December, 1953, 10 months after Syme amputation. Walks without crutches or cane. Patient considers present status of the right lower extremity as good as it was prior to developing the necrosis of that foot. It supports the amputated left leg as well. He can walk about 10 steps around house without the Syme prosthesis. He thinks it is far better than the below-knee amputation he had on the right. He is fully active and expects to return to work soon.

CASE 5.—J. J. L., Boston V.A. Hospital, R#8591. Aged 51 years. Admitted April 11, 1953, discharged May 27, 1953.

Diagnosis.—Arteriosclerosis obliterans. Diabetes mellitus.

History.—3 years before—ulcer of left great toe which healed on conservative treatment.

11 months before—corn on left small toe.

1 month before—corn opened and then turned black.

Local Examination.—Left lower extremity: Necrosis of dorsum forefoot extending from the interdigital area between fourth and fifth toes.

Lowest pulse—popliteal. Oscillations in calf 1+ (on basis of 4+).

Fig. 1*A*.—Case 5. Appearance of foot preoperatively.

Right lower extremity: Asymptomatic. Pulses normal.

Clinical Course.—Necrosis spread after admission, but cellulitis decreased.

April 27, 1953—Syme amputation, left.

3 weeks postoperative—patient up on crutches.

5 weeks postoperative—use of prosthesis started.

8 weeks postoperative—returned to work as a shipping clerk.

4 months postoperative—developed pressure ulcer lateral aspect of stump "from attempting to wear an ordinary shoe." This healed in 2 months of leaving off prosthesis and using crutches.

Last Follow-up.—December, 1953, 9 months after Syme amputation. Walks normally without cane. Works full time as shipping clerk. Can use the stump around the house without a prosthesis but does not often do so.

CASE 6.—W. K., Cushing V.A. Hospital, R#43507. Aged 56 years. Admitted June 9, 1953, discharged Sept. 22, 1953.

Diagnosis.—Arteriosclerosis obliterans, diabetes mellitus.

Fig. 1*B*.—Appearance of stump six months postoperatively.

History.—4 years before—diabetes mellitus diagnosed.

1½ years before—cerebral vascular accident without residual.

8 months before—gangrene following corn on right great toe.

6 months before—right lumbar sympathectomy, left lumbar sympathectomy.

2 months before—amputation of right great toe followed by spread of infection and gangrene.

Local Examination.—Right lower extremity: Lowest palpable pulse was the femoral. Calf oscillations 1+ (basis 4+). Gangrene of amputation site of right great toe.

Left lower extremity: Lowest papable pulse was the femoral. Calf oscillations 2+.

Clinical Course.—Aug. 20, 1953—Syme amputation, right.

21 days postoperative—walking on crutches.

1 month postoperative measured for prosthesis. Discharged from hospital with primary healing.

4 months postoperative wearing prosthesis. This was delayed because of an infection in left lumbar sympathectomy wound.

Last Follow-up.—Jan. 4, 1954, 6 months after Syme amputation. Doing well on prosthesis. Ultimate functional result not yet determined.

Fig. 1*C.*—Wearing prosthesis six months postoperatively.

DISCUSSION

It is apparent from the protocols that the operation has been performed only in carefully selected cases. That the criteria for selection of cases have been good is evidenced by the fact that there have been no failures. Only 2

per cent of amputations performed in the lower extremity for vascular disease (three of 154 amputations in a six-year period at the Veterans Administration Hospital, West Roxbury) were Syme amputations. When the indications present themselves, however, they seem reasonably clear, namely, well-stabilized necrotic lesions of the foot penetrating deeply enough to require some sort of amputation, situated at a point too far proximal to allow for amputation at the transmetatarsal or tarsometatarsal (Lisfranc) level, yet far enough distal so that the skin is normal at the point where the Syme incision is made. It is understood, as in the case of the transmetatarsal amputation, that the patient must not be of a degree of infirmity which will preclude rehabilitation to ambulation if the operation is successful. It is to be noted that we have not considered amputations for ischemic lesions between the level of the transmetatarsal or tarsometatarsal and the Syme. Although healing is theoretically possible if the principles of operating in the ischemic foot are observed, such amputations require skin flaps of a length which provide little superiority over the transmetatarsal in respect to opportunity to amputate proximal to gangrene, and the stumps are reputedly of a degree of ungainliness which, being ischemic, would be unlikely to stand up under even minimal trauma.

Assessment of the degree of impairment of circulation in the group under study (which has been done entirely on clinical grounds) shows it to be slightly less marked than the average of all patients entering the hospital with ischemic lesions of the toes. Popliteal pulses were palpable in five of the six. But that definite ischemia was present in all is evidenced by the facts that foot pulses were palpable in none, that oscillations were nearly absent in the calves of three of the four in whom they were measured, and that four of the six had had failure, due to ischemia, of recently performed amputations at the transphalangeal or transmetatarsal level. If clinical appraisal of the collateral circulation in terms of the level of ischemia as evidenced by rubor on dependency shows it to be adequate below the heel, a significant degree of diminution of pulses or oscillations should not be a deterrent to the operation.

Prior lumbar sympathectomy had been performed in four of the six cases. Indication for sympathectomy was hope of improvement of collateral circulation to the extent of promoting healing of the original ischemic lesion. It had not been thought that it might promote healing of a Syme amputation which was not at that juncture envisaged. Here, as in the case of the preparation for the transmetatarsal amputation, we cannot state that lumbar sympathectomy should be a preoperative routine.[2]

It is not proper to imply that, because of the salvage of two limbs by the Syme amputation following unsuccessful transmetatarsal amputation, all unsuccessful transmetatarsal are *ipso facto* candidates for the Syme. Many transmetatarsal amputations which are unsuccessful to the point of developing necrosis of part of the suture line without separation thereof are well treated conservatively with eventual separation of the slough and healing. For those with marked separation of the wound or with necrosis advancing into the

tendons there is little hope of such an event, and a Syme amputation should be considered provided a local revision with further bone excision at the transmetatarsal level followed by primary closure[1] is not possible.

TECHNIQUE

No useful points of technique can be mentioned which have not already been laid down. Syme,[3] most of whose patients were suffering from tuberculosis of the bones of the foot, left few, if any, practical points unmentioned. More modern accounts are those of Wilson[5] and Alldredge,[4] who emphasize the desirability of removal of all the articular surface of the lower tibia, a maneuver not used by Syme except in instances of disease involving the ankle joint. In this respect we have followed the more modern practice. We feel that carefully applied adhesive support of the stump flap is desirable for at least two weeks in order to prevent its slipping sideways and to avoid accumulation of fluid beneath it.

COMPLICATIONS

These have been few and minor. One patient (Case 2) accumulated sufficient fluid under the flap to require one aspiration. One patient (Case 4) developed a pressure ulcer on the stump flap four months after operation and two months after returning to work due to a misguided attempt on his part to wear an ordinary shoe. The area healed in two months.

REHABILITATION

All the patients are walking to an extent which is adequate for their individual economic and social needs. None is disabled to a degree greater than existed prior to the illness which led to the Syme amputation. Two of the six are working full time. One, the man of 33 who has a Gritti-Stokes amputation in the opposite extremity, has a job to which he is planning to return. He considers the Syme amputation superior to the below-knee amputation he had at an earlier date on the opposite side.

With regard to walking without the prosthesis around the house for short distance and emergency needs, two of the six do so freely, three others (including the one with the contralateral Gritti-Stokes amputation) can do so but prefer not to, and one is unable to do so because of general unsteadiness and lack of confidence which he exhibited even before the amputation. Four of the patients prefer to use a cane when walking with the prosthesis away from home.

We have not as yet been presented with the decision for the performance of the Syme amputation on a woman. We hope we will not, because we believe ourselves unable to understand the apparent preference of most women for the more disabling below-knee amputation over the cosmetically undesirable, but less unwieldy, prosthesis of the Syme.

SUMMARY

1. Six Syme amputations have been performed for ischemic lesion of the foot.

2. The indications for the amputation and principles of its management are similar to those for a transmetatarsal amputation given a more proximal level of necrosis.

ADDENDUM

Since the paper was submitted for publication five additional Syme amputations have been undertaken using indications less conservative than those described. Two of these have failed and the patients have received satisfactory higher amputations. This added experience has confirmed our impression that the patients must be as carefully selected as those for the transmetatarsal amputation.

Of the amputation stumps in the six patients here reported all but one remain as described. In that one, recurrent blistering and areas of necrosis occur around the stump due to misuse of the prosthesis by the patient who is the same individual (J. J. L.) who developed an ulcer from wearing an ordinary shoe early in his postoperative course.

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